

Energy-Related Environment Research

ACTIVE CONTROL FOR REDUCING THE FORMATION OF NITROGEN OXIDES IN INDUSTRIAL GAS BURNERS AND STATIONARY GAS TURBINES

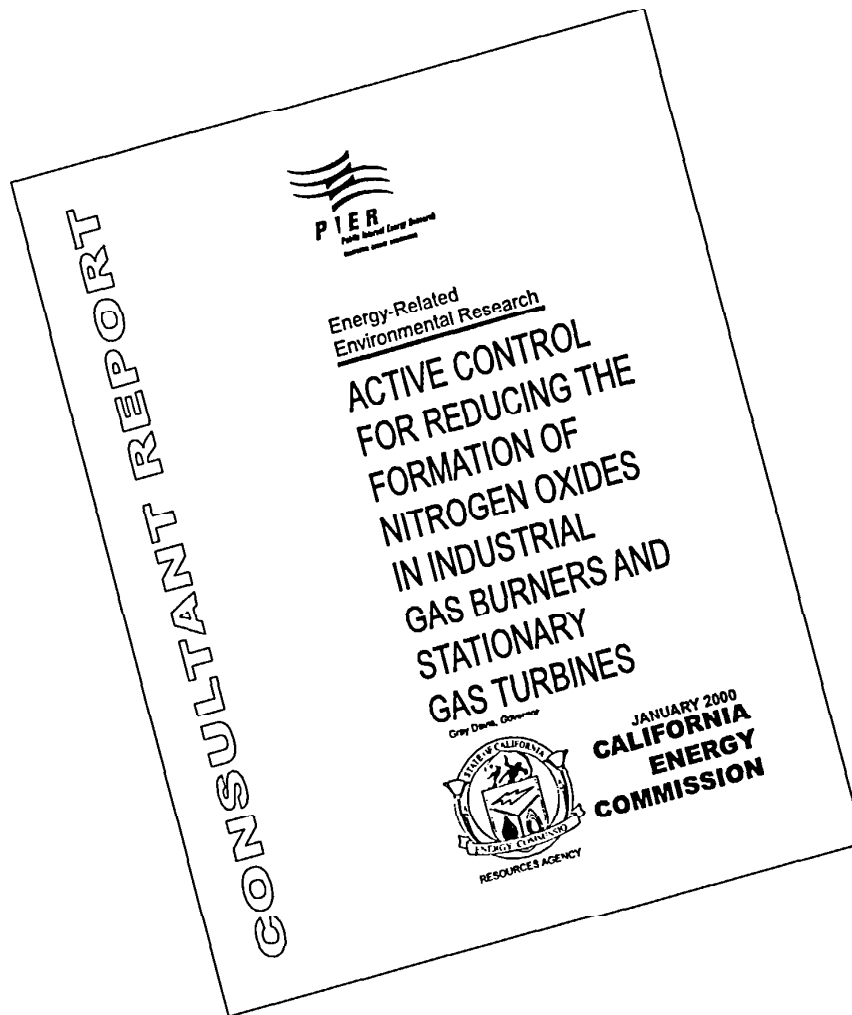
Gray Davis, Governor



RESOURCES AGENCY

JANUARY 2000
CALIFORNIA
ENERGY
COMMISSION

P600-00-009



CALIFORNIA ENERGY COMMISSION

Prepared for:
**CALIFORNIA ENERGY
COMMISSION**

Prepared by:
John Samuelson, UCI, *Principal Investigator*
Matt Miyasoto, UCI, *Principal Investigator*

**CALIFORNIA
INSTITUTE FOR
ENERGY EFFICIENCY**
James Cole, *CIEE Technical Liaison*

Contract No. 500-97-013
Project No. 09

Contract Amount: \$335,000

Matthew Layton, *Project Manager*
ENVIRONMENTAL OFFICE

Bob Therkelson, *Deputy Director*
**ENERGY FACILITIES SITING &
ENVIRONMENTAL PROTECTION
DIVISION**

Gary Klein, *Contract Manager*
**ENERGY TECHNOLOGY
DEVELOPMENT DIVISION**

Legal Notice

This report was prepared as a result of work sponsored by the California Energy Commission (Commission). It does not necessarily represent the views of the Commission, its employees, or the State of California. The Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Commission nor has the Commission passed upon the accuracy or adequacy of this information in this report.

Acknowledgements

This work was graciously funded with foresight by the California Energy Commission under contract number 500-97-013. Gratitude is expressed to two Commission representatives: Mr. Matthew Layton, the project liaison, for his guidance during the course of the project, and Mr. Gary Klein for his help in bringing this report to conclusion. Acknowledgement and thanks are also extended to Dr. James Cole of the California Institute for Energy Efficiency for his support and help in securing and administering this project. The contributions of Mr. Trevor Demayo and Mr. Rene Flores are also greatly appreciated.

TABLE OF CONTENTS

Section	Page
PREFACE.....	VIII
EXECUTIVE SUMMARY.....	1
ABSTRACT.....	3
1.0 INTRODUCTION	5
1.1 Goals and Objectives	5
1.2 Approach.....	7
1.3 Background.....	7
1.4 Previous Work (CIEE Program)	9
2.0 FACILITIES	13
2.1 Industrial Burner Test Stand	13
2.1.1 Model Industrial Burner	15
2.1.2 Commercial Boiler Burner	16
2.2 Gas Turbine Combustor Test Stand	16
2.3 Diagnostics	18
3.0 RESULTS	19
3.1 Identification of Fast Feedback Sensors	19
3.2 Suitability of Selected Sensors.....	20
3.2.1 Chemiluminescence	21
3.3 Approach.....	21
3.4 Results.....	24
3.4.1 Dynamic Pressure Sensor and Acoustic Microphone.....	30
3.5 Upgrade of Active Control Software	32
3.6 SGAC Demonstration on Industrial Burners	34
3.6.1 Model Burner	34
3.6.2 Boiler Burner.....	36
3.7 SGAC Demonstration on Gas Turbine Combustor.....	40
3.7.1 Fast Feedback Sensors Development	40
3.7.2 SGAC Demonstration	44
3.8 Technology Transfer.....	46
4.0 CONCLUSIONS AND RECOMMENDATIONS	47
4.1 Outcomes and Conclusions	47
4.1.1 Identify Fast Feedback Sensors	47
4.1.2 Determine Suitability of Selected Sensors	47
4.1.3 Upgrade Existing Active Control Software.....	48
4.1.4 Demonstrate Fast Sensors and Software on Two Industrial Burners	49
4.1.5 Demonstrate Fast Sensors and Software on Gas Turbine.....	50
4.1.6 Task 8: Technology Transfer	51
4.2 Recommendations and Commercialization Potential	51
4.2.1 Sensor Recommendations	51

4.2.2	Software Recommendations.....	51
4.2.3	Implementation Recommendations.....	52
4.2.4	Commercialization Potential	52
5.0	REFERENCES.....	53

List of Figures

Figure	Page
Figure 1: Active Control Schematic	7
Figure 2: NO _x and CO Emissions Trade-off.....	9
Figure 3: NO _x and CO Emissions for Model Industrial Burner with Co-swirl Fuel Injection	10
Figure 4: NO _x and Efficiency Functions	11
Figure 5: Model Industrial Burner Performance.....	11
Figure 6: First Generation Active Control on Model Industrial Burner	12
Figure 7: Industrial Burner Test Stand	14
Figure 8: Model Industrial Burner	15
Figure 9: Coen Scaled-Down Commercial Boiler Burner (QLN).....	16
Figure 10: Gas Turbine Combustor with Adaptive Fuel Injection	17
Figure 11: Gaseous Emissions Sampling Schematic.....	18
Figure 12: Feedback Sensors Considered.....	19
Figure 13: Chemiluminescence Experimental Setup	22
Figure 14: Optical Layout.....	23
Figure 15: Fiber Optic Locations.....	24
Figure 16: Co-swirl and Counter-swirl Injector Emissions	24
Figure 17: Chemiluminescence Profiles at 10% Excess Air	25
Figure 18: OH and CO ₂ Average and Fluctuating Chemiluminescence for the Co- swirl Injector	26
Figure 19: OH and CO ₂ Average and Fluctuating Chemiluminescence for the Counter-swirl Injector	27
Figure 20: Chemiluminescence Correlation to NO _x Emissions.....	27
Figure 21: OH and CO ₂ % Fluctuations for Co-swirl Injector	28
Figure 22: OH and CO ₂ % Fluctuations for Counter-swirl Injector.....	29
Figure 23: Chemiluminescence Correlation to CO Emissions	29
Figure 24: Placement of Dynamic Pressure Sensor and Microphone	30
Figure 25: Frequency Response of Model Industrial Burner.....	31
Figure 26: Peak Frequency Response between 12 and 102 Hz for Counter-swirl Injector	31
Figure 27: Second Generation Active Control Concept	32
Figure 28: SGAC System Schematic.....	33
Figure 29: Model Burner Performance Map	34

Figure 30: SGAC for Model Burner with Exhaust Emissions Sensor.....	35
Figure 31: SGAC for Model Burner with Chemiluminescence Sensor	36
Figure 32: Boiler Burner Performance Map	37
Figure 33: SGAC for Scaled-Down Boiler Burner with Exhaust Emissions Sensor [① start, ② finish].....	37
Figure 34: Boiler Burner Performance Map with System Efficiency Factor.....	38
Figure 35: SGAC for Scaled-Down Boiler Burner with Exhaust Emissions Sensor and System Efficiency Factor	39
Figure 36: SGAC for Scaled-Down Boiler Burner with Chemiluminescence Sensor and System Efficiency Factor	39
Figure 37: Fiber Optic and Microphone Placement for Gas Turbine	40
Figure 38: Gas Turbine Combustor Exhaust Emissions.....	41
Figure 39: Gas Turbine Combustor Performance	41
Figure 40: Gas Turbine Combustor Chemiluminescence Measurements	43
Figure 41: Chemiluminescence Estimation of Emissions	43
Figure 42: Gas Turbine Combustor Acoustic Measurements	44
Figure 43: Sensor Response Times	44
Figure 44: SGAC for Gas Turbine Combustor with Exhaust Emissions Sensor.....	45
Figure 45: SGAC for Gas Turbine Combustor with CO ₂ Sensor.....	45
Figure 46: SGAC for Gas Turbine Combustor with Acoustic Sensor.....	46

List of Tables

Table	Page
Table 1: National and California Ambient Air Quality Standards.....	8
Table 2: Fuel and Air Supply Flows.....	13
Table 3: Selected Sensor Attributes.....	20
Table 4: Chemiluminescence Reactions and Dominant Wavelength Emissions.....	21

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately \$17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Active Control for Reducing the Formation of Nitrogen Oxides in Industrial Gas Burners and Stationary Gas Turbines, one of nine projects conducted by the California Institute for Energy Efficiency. This project contributes to the Environmentally-Preferred Advanced Generation program.

For more information on the PIER Program, please visit the Commission's Web site at: <http://www.energy.ca.gov/research/index.html> or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Low emissions technologies are driving the development of new generation stationary power sources. The next generation industrial burners and stationary gas turbine combustors will be required to maintain extremely low levels of nitrogen oxides (NO_x) and carbon monoxide (CO) emissions, previously thought unattainable. In order to attain these levels of reduced emissions, combustion system will require active control systems to automatically achieve low emissions with simultaneous high efficiency regardless of changes in load, gas composition, or hardware deterioration.

The purpose of this project is to address this challenge, namely, to develop technologies (and associated scientific and applications-oriented knowledge) to attain and maintain energy-efficient operation of natural gas industrial burners and stationary gas turbines with ultra-low emissions of NO_x . The core component is a closed loop combustion control with advanced sensors, including demonstrations applied to industrial burners and gas turbines. Specifically, the program addresses (1) the further development of the active control system on a boiler burner, and (2) the proof-of-concept of the active control on a gas turbine, both applications targeting the energy/electrical production market.

The project goals were divided into discrete objectives, or tasks, upon which to build the second-generation active control (SGAC) program. These objectives were to (1) identify fast feedback sensors, (2) determine the suitability of these fast sensors for industrial burners and gas turbine applications, (3) upgrade the active control software for ease-of-use and fast feedback capability, (4) refine the use of the fast sensors and new software on industrial burners, (5) demonstrate the fast sensors and new software on a gas turbine combustor, and (6) transfer the technology concept to the combustion community.

An extensive review was conducted to identify the state-of-the-art for fast sensor technologies relating to NO_x and CO measurement. A criterion was developed based on intrusiveness, time response, ease-of-use, robustness, and cost to narrow the field and identify candidates for investigation. Based on this criterion, three sensor technologies were selected: dynamic pressure sensor, acoustic microphone, and chemiluminescence.

The three sensor technologies were evaluated on an industrial burner test stand. Of these three, flame radical chemiluminescence of OH and CO_2 showed the most promise for both the industrial burner and gas turbine trials in terms of NO_x and CO emissions correlations. The acoustic response measured via an external microphone displayed a good correlation to performance for the gas turbine combustor. Due to the low temperature threshold and need to be very close to the reaction, the dynamic pressure sensor was disregarded as a fast active control feedback sensor.

The active control software was upgraded using a modular strategy to allow for easier updates, enhanced portability, and clearer programming. The data acquisition and controls modules were coded in *LabView*. The algorithm modules were coded in two different programs to determine flexibility and ease-of-use; *Fortran* was used for the industrial burner tests, and *Excel Visual Basic* was used for the gas turbine tests. More work is required to enhance the user

interface and make the modules more general. However, the program worked well for both the burner and gas turbine experiments.

Once the software was completed, the sensors were combined with the SGAC program to form an integrated SGAC *system*. Trials were conducted on three different systems: a model industrial burner, a scaled-down Coen boiler burner, and a gas turbine combustor. Emissions analyzers were used as the baseline feedback sensor to simulate existing continuous emissions monitoring systems available in industry. The baseline industrial burner optimizations ranged from 9 to 16 minutes using the exhaust emissions analyzers. Implementing the faster OH chemiluminescence feedback sensor, optimization times were reduced by at least 30% in all cases.

For the gas turbine SGAC tests, the chemiluminescence sensor allowed optimization over three times faster than with the emissions analyzers. An additional sensor was also attempted on the gas turbine combustor using the gas fluctuating component of the acoustic signal. Although the acoustic signal provided extremely fast optimization (over six times faster than with the emissions analyzers), it is suspected that the acoustic signature is system specific; more research is required to ensure the validity of this sensor over a broad range of applications and conditions.

The final objective of the project was to transition these experimental results to the combustion community. This was accomplished via three presentations of the project results at two different combustion conferences and through personal interaction with industrial burner and gas turbine manufacturers at these conferences.

The successes of this research are encouraging and timely due to the current state of the electric industry in California. With deregulation, larger centralized power plants will compete with smaller distributed power producing units. These power plants will likely be dispatched to follow the local loads, which would mean constant cycling of power and firing rate. If harmful pollutant emissions are to be minimized, an automatic and optimized control system is therefore required. This research provides the building blocks for just such a system.

Abstract

A comprehensive active control strategy was successfully demonstrated for industrial gas burners and stationary gas turbines during this one-year project. Active control provides the continuous performance optimization and control of the combustion application through feedback sensors, robust computer optimization algorithms, and computer control of the burner or gas turbine. Modern combustion systems will require active control to automatically achieve low emissions with simultaneous high efficiency and stability, regardless of changes in load, gas composition, or hardware deterioration.

The overall goals of this project were to further develop the active control methodology established for industrial burners, and then demonstrate the proof-of-concept for active control on a gas turbine. The major objectives identified to meet these goals were to (1) identify fast feedback sensors, (2) determine the suitability of these fast sensors for industrial burners and gas turbine applications, (3) upgrade the active control software for ease-of-use and fast feedback capability, (4) refine the use of the fast sensors and new software on industrial burners, (5) demonstrate the fast sensors and new software on a gas turbine combustor, and (6) transfer the technology concept to the combustion community. The fast sensors that were investigated and selected for trials were fiber optic collection of reaction chemiluminescence, an acoustic microphone, and a piezoelectric dynamic-pressure sensor. The active control computer system consisted of commercial software and hardware (National Instruments *LabView* and data acquisition boards) in conjunction with simple optimization techniques. Control of the combustion processes was achieved using mass flow controllers to optimize the fuel injection and airflows at different operating conditions.

By completing all six of these objectives, the project goals were successfully accomplished. A second-generation active control system using fast sensors was demonstrated on two different sized industrial burner systems and a gas turbine combustor. The successes of this research are encouraging and timely due to the current state of the electric industry in California. Central station and small, distributed generators will compete in the deregulated electricity market, which could mean constant cycling of firing rate while still complying with some of the strictest air pollution regulations in the country. As a result, this technology is poised to play an integral role in California's power generation future.

1.0 Introduction

Low emissions technologies are driving the development of new generation stationary power sources. The next generation industrial burners and stationary gas turbine combustors will be required to maintain extremely low levels of nitrogen oxides (NO_x) and carbon monoxide (CO) emissions, previously thought unattainable. Current state-of-the-art is to use back-end clean up of the exhaust stream with selective catalytic reduction (SCR) or a similar technique. This method, although effective, is costly and inelegant. Alternatively, burner and gas turbine combustor manufacturers are striving to reduce the pollutants at the source by adopting a lean-premixed or partially premixed fuel and air strategy; the challenge with these systems is that CO can increase and stability can decrease along with the reduction in NO_x .

A major program, established in 1991 at the University of California Irvine Combustion Laboratory (UCICL) and funded by the California Institute for Energy Efficiency (CIEE), has focused on fuel and air mixing scenarios that can address this challenge of simultaneously reducing NO_x and CO emissions. An important aspect of this program has been the development of *active control*, which is a closed-loop feedback control system for the combustion process, to automatically attain and maintain energy efficient and low emission operation of natural gas industrial burners. The active control technology was successfully demonstrated to continually adjust the combustion system for high performance despite changes in load. The two major recommendations resulting from these initial tests identified the need for (1) faster response-time emissions and stability feedback sensors and (2) demonstrations on different systems.

The development of the second-generation active control system to address these two needs was thus conducted as an 18-month project sponsored by the California Energy Commission. The details of this project will be described in the following report.

1.1 Goals and Objectives

The two major goals of the project were to

- Further refine and enhance the active control methodology (and associated scientific and applications-oriented knowledge) on a boiler burner and
- Demonstrate the proof-of-concept of the active control methodology on a gas turbine, with both combustion applications, industrial burners and stationary gas turbines, targeting the energy/electrical production market.

The specific objectives identified to meet these goals are outlined below (with the specific tasks as identified in the proposal provided in the parentheses).

1. Identify fast feedback sensors for industrial combustion systems that can be located near the reaction (Task 3),
2. Determine the suitability of these fast sensors for industrial burners and gas turbine applications (Task 3),

3. Upgrade the existing active control software to be more user/designer friendly and incorporate fast response sensors (Task 4),
4. Demonstrate the fast response sensors and new software on two industrial burners (Task 5), and
5. Demonstrate the fast response sensors and new software on a model gas turbine combustor (Tasks 6 and 7).
6. Transfer the technology to the combustion community.

All of these broad goals were achieved over the program duration and represent noteworthy contributions to the industrial combustion community. This project has allowed the continuation and expansion of the promising work initiated under the CIEE core program. With the current trend toward lean burn technologies to achieve ultra low emissions, an automatically optimizing and stabilizing system will allow for higher energy efficiencies while balancing regulatory limitations. In regulatory intensive locations such as southern California, this type of system could play a major role in allowing businesses to meet emissions while remaining competitive. This is especially true for systems that cycle loads frequently, such as gas turbine generators when peak-following. As such, this research is timely and necessary to maintain and expand business opportunities in order to keep pace with environmental concerns.

The total project award of \$335,000 was expended on budget through December 1999.

1.2 Approach

There are three major components required to conduct active control optimization for combustion systems: ① a controllable combustion device, ② an array of feedback sensors, and ③ the computer logic to process the feedback information from the sensors and change the combustion device. A schematic of this strategy is shown in Figure 1. This research project focused on the development of the fast time response feedback sensors, integration of these sensors into an active control system, and demonstration of the technology on different combustion applications, specifically industrial burners and gas turbine systems.

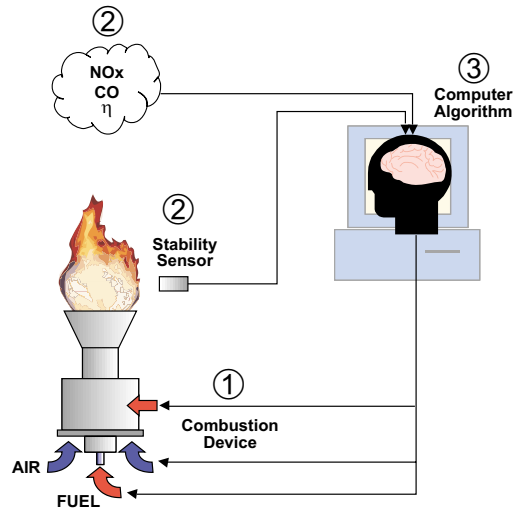


Figure 1: Active Control Schematic

The following sections describe the need for such combustion control systems and the previous work conducted in this effort.

1.3 Background

The two main pollutants of concern in this research are nitrogen oxides and carbon monoxide. Although both pollutant emissions are harmful in their own right, they are also key factors in ozone production. Oxides of nitrogen play an important role in air quality since NO is the principal precursor to NO₂ in the atmosphere, and NO₂ is the *sole* source of anthropogenically produced ozone (Finlayson-Pitts and Pitts, 1993). Measurements indicate that for every NO₂ molecule emitted, 4 to 8 molecules of O₃ are produced (Trainer *et al.*, 1993). Since ozone levels in the troposphere are steadily increasing from background or “clean” levels, this implicates combustion derived NO₂ as the primary culprit.

Carbon monoxide is a product of incomplete combustion and has economic implications since inefficient combustion translates to higher fuel consumption to achieve a target heat release. However, CO also plays a role in NO to NO₂ conversion in the atmosphere and can thereby contribute to ozone formation. The following sections discuss the societal implications of increased CO, NO_x, and O₃ levels in the troposphere, the formation mechanisms of CO and NO_x during combustion, and the transformation of NO_x to O₃ in the atmosphere.

Increased CO, NO₂, and O₃ concentrations in the atmosphere are of concern due to their adverse effects on plants and animals. Carbon monoxide is especially dangerous since it replaces oxygen in the bloodstream, causing headache, reduced mental acuity, vomiting, coma, and even death at acute exposure levels (Seinfeld, 1986). Detrimental health effects also arise from acute exposure to O₃ and NO₂ in the form of shortness of breath, labored breathing, coughing, chest tightness, and stinging of the eyes (McKee and Rodriguez, 1993). The US Office of Technology Assessment has estimated that the cost of treating the short term health effects caused by ozone inhalation is \$0.5 to \$4 billion per year, and the crop damage due to ozone is estimated at \$1 to \$2 billion per year (Sillman, 1993). As a consequence of these harmful effects, the federal government has established exposure limits based on preserving public health and welfare. California has enacted more stringent one hour exposure limits due to the higher concentrations experienced in several California air districts. The National and California Ambient Air Quality Standards for CO, NO₂, and O₃ are reported in Table 1. For more detailed information on the health, material, and plant effects caused by CO, NO_x, and ozone exposure, the reader is directed to Seinfeld (1986) and US EPA (1993).

Table 1: National and California Ambient Air Quality Standards

<i>Species</i>	<i>Type of Average</i>	<i>National</i>	<i>California</i>
CO	1 hour 8 hour	35 ppm 9 ppm	20 ppm 9 ppm
NO ₂	1 hour	0.053 ppm *	0.25 ppm
Ozone	1 hour 8 hour	0.12 ppm 0.08 ppm	0.09 ppm

* National limit defined only as an annual arithmetic mean

On a global scale, tropospheric ozone production is significant due to (1) the increasing concentration in the atmosphere and (2) its role in radiative forcing and climate change. There have been numerous studies conducted which have established that ambient ozone concentrations are increasing in the atmosphere (e.g., Volz and Kley, 1988; and Brühl and Crutzen, 1989). Due to these increasing levels, researchers have modeled the radiative forcing effect and concluded that ozone may contribute to the “greenhouse effect” with an increase of 0.0017 to 0.5°C in the global mean temperature (Lacis, Wuebbles, and Logan, 1990; Fishman, 1991; Johnson, Henshaw, and McInnes, 1992). The magnitude of this radiative forcing is 13 to 50% of the forcing attributable to CO₂ (Wang and Zhaung, 1989 and Lacis *et al.*, 1990). The reduction of ozone precursors is thus an important regional *and* global goal.

The task of reducing NO_x and CO simultaneously is challenging since both pollutants are minimized under different conditions. Operation at lower reaction temperatures reduces NO_x emissions but can also increase CO emissions and decrease stability. Conversely, high reaction temperatures will promote the oxidation of CO to CO₂ but will also produce copious amounts of NO_x. To combat this inherent trade-off, industrial systems operate within a limited range of

excess air levels in order to minimize NO_x emissions without blowing out the reaction or increasing the CO emissions due to quenching. To ensure that blowout does not occur, a sufficient safety margin is also incorporated into the operating limits. These characteristics are shown schematically in Figure 2.

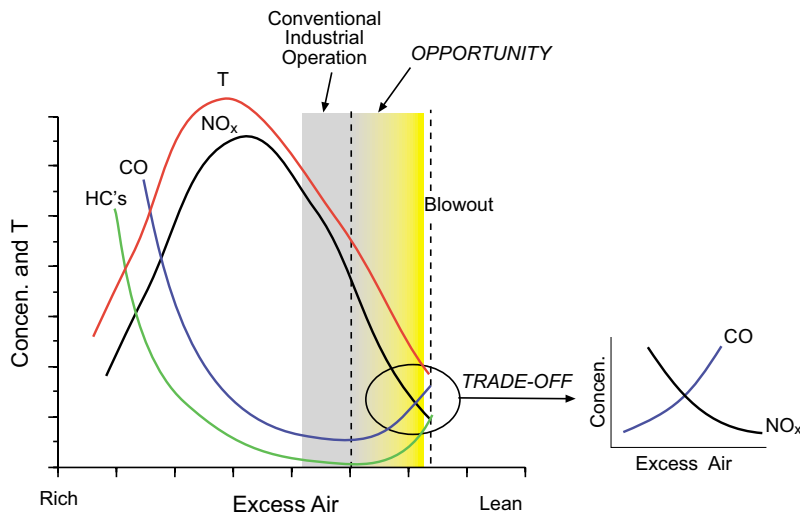


Figure 2: NO_x and CO Emissions Trade-off

As such, a window of opportunity exists whereby lower NO_x emissions can be achieved if faster stability and emissions measurements are provided to safeguard against blowout and higher CO emissions. An *active control* system can be implemented to constantly assess the emissions performance and automatically move the system into better performing regions when changes occur in the system. Changes in the system can occur due to hardware degradation, changes in fuel composition, or load cycling. The next section describes the previous work leading up to this project.

1.4 Previous Work (CIEE Program)

This Energy Commission sponsored project was based on an extension of the CIEE core program, whose goals were to identify NO_x production mechanisms in industrial burners and develop active control strategies in these burners. The following section provides the major, relevant findings of the CIEE program, which puts this current program in perspective by establishing the foundation of this research.

CIEE Findings

In order to provide continual, high performance (low NO_x and low CO emissions), energy efficient operation of industrial combustion systems, constant monitoring of the reaction is required with real-time adjustment capability. The goals of the CIEE core program, in this respect, were to *attain* and *maintain* low NO_x , low CO, high performance conditions in a model, industrial burner.

The initial challenge was to determine whether conditions even existed where NO_x and CO emissions could be simultaneously minimized within the reaction without resorting to post-flame cleanup techniques (e.g., selective catalytic reduction) or conventional diluent strategies (e.g., flue gas recirculation or fuel staging). As discussed in the Background section, however, NO_x and CO emissions are often opposed in conventional burners, i.e., when NO_x emissions are high, CO emissions are low and when CO emissions are high, NO_x emissions are low. This is exemplified in Figure 3, which shows the NO_x and CO emissions for a model industrial burner with co-swirl fuel injection. The regions of low NO_x (blue and purple colors in left plot) correspond to regions of high CO emission (orange and red colors in right plot).

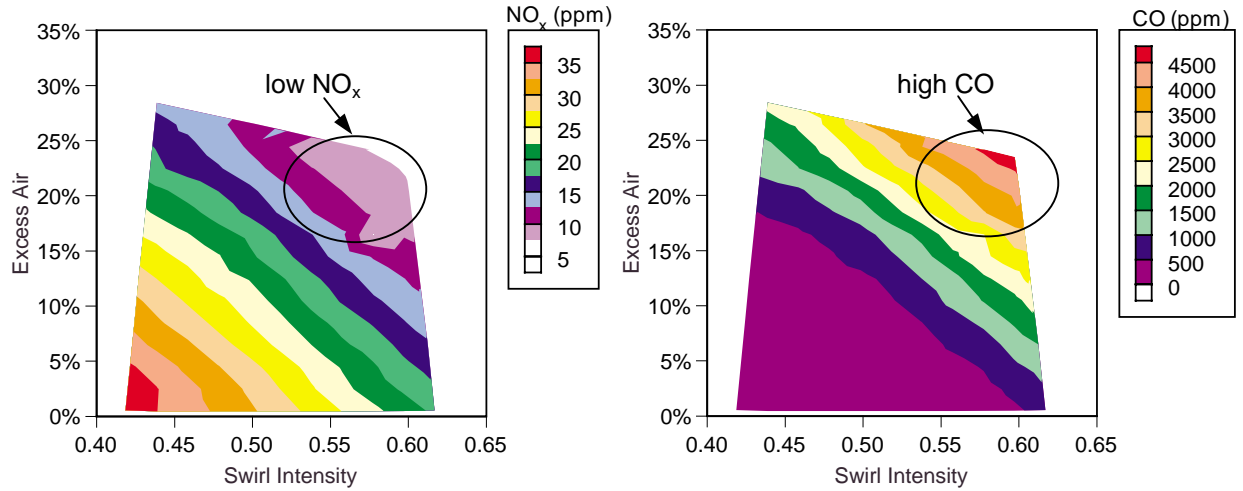


Figure 3: NO_x and CO Emissions for Model Industrial Burner with Co-swirl Fuel Injection

From these plots, it is difficult to determine which condition provides the optimum in terms of NO_x and CO emissions. In order to address this trade-off quantitatively, a cost function was developed which allows the systematic comparison of conditions to numerically assess their performance. The form of this performance function is shown below

$$J = w \cdot f(NO_x) + w \cdot g(\eta)$$

where J is the performance index, w is a weighting factor, $f(NO_x)$ is the NO_x contribution and $g(\eta)$ is the CO (combustion efficiency) contribution to the performance. For all the tests conducted in this program, NO_x and combustion efficiency was equally weighted. The functions of f and g are plotted in Figure 4.

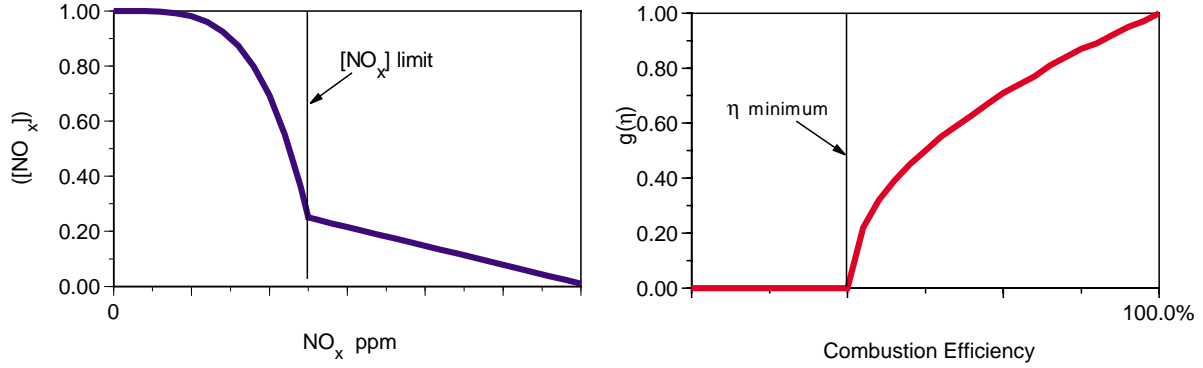


Figure 4: NOx and Efficiency Functions

Using the performance function, the emissions are used to calculate the performance indices and replotted in Figure 5. The plot identifies a diagonal ridge of preferred performance sloping down from low swirl-high excess air to high swirl-low excess (red color in plot).

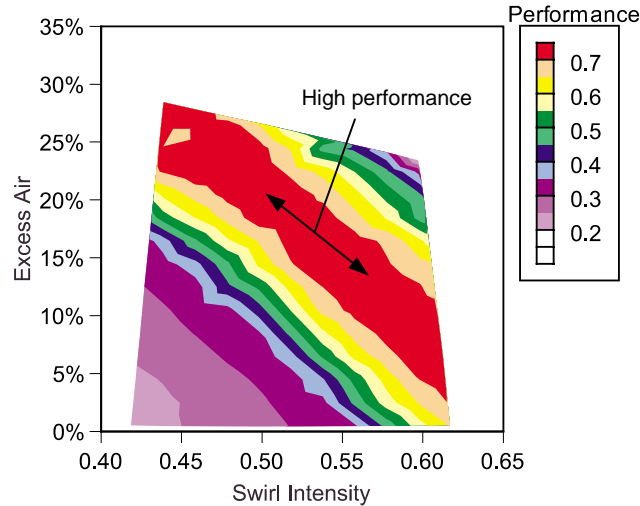


Figure 5: Model Industrial Burner Performance

The initial active control demonstration utilized a direction-set (Powell's method) optimization algorithm. This program was able to optimize the model industrial burner along this ridge of high performance, as shown in Figure 6 (the black lines represent the search history).

Although the initial active control system was able to optimize the search space, several needs were identified to improve the technology. The first major conclusion was that the time response of the system was too slow due to the use of stack emissions analyzers for the feedback sensors. In order to ensure steady-state emissions samples, the program waited two minutes after moving to a new condition and then sampled the emissions and calculated the performance. Further, the computer algorithm was programmed in *Visual Basic*, which did not allow the user to easily change parameters. Finally, to demonstrate its utility, the active control technology must be applied to other stationary combustion systems, e.g. boiler burners and gas turbine combustors.

The current project sponsored by the Energy Commission has allowed the investigation and resolution of these challenges. The following section provides the details on the facilities utilized at the UC Irvine Combustion Laboratory (UCICL).

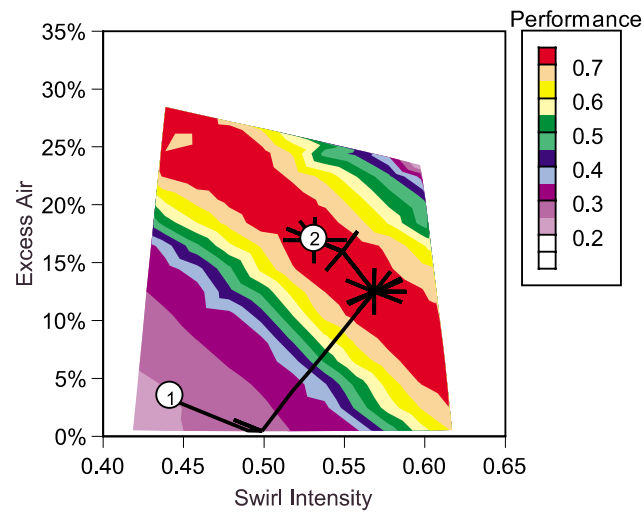


Figure 6: First Generation Active Control on Model Industrial Burner

2.0 Facilities

Two different combustion applications were targeted for this program: industrial burners and stationary gas turbines. As such, two different test facilities were utilized. Each facility is described in the following sections.

2.1 Industrial Burner Test Stand

The industrial burner test facility is designed to conduct detailed measurements and proof-of-concept investigations on scaled-down industrial burner hardware. The facility has a large range of metering capabilities for air and natural gas with computer control of flow ranges shown in Table 1. These flows provide a maximum firing rate of 500,000 Btu/hr at an excess air level of 77%.

Table 2: Fuel and Air Supply Flows

	Number of Lines	Pressure psi	Flow Rates scfm
Natural Gas	3	40	2.3
			8.0
			8.0
Air	3	150	35
			35
			80

The furnace enclosure is specially designed to allow full optical access of the reaction for visualization and laser diagnostic measurements. A schematic of the test facility is shown in Figure 7.

The two industrial burners utilized for this program were the generic, model industrial burner and the Coen-designed, scaled-down commercial boiler burner.

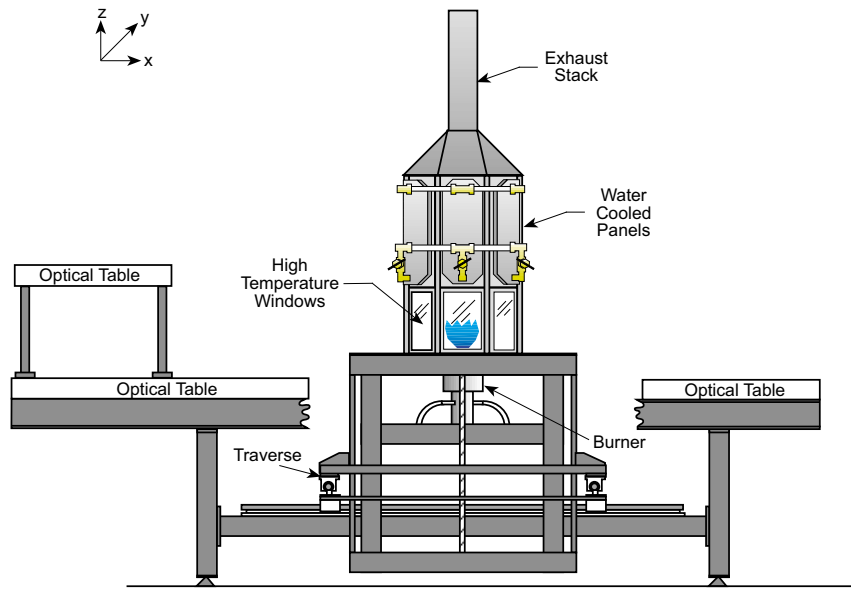


Figure 7: Industrial Burner Test Stand

2.1.1 Model Industrial Burner

The model industrial burner is a swirl stabilized, co-axial, up-fired natural gas burner. The air swirl is adjusted by varying the ratio of axial air (\dot{m}_a) to swirling air (\dot{m}_ϕ). The swirl intensity is defined as S' , represented as the square of the swirl air flow divided by the total air flow:

$$S' = \left(\frac{\dot{m}_\phi}{\dot{m}_a + \dot{m}_\phi} \right)^2$$

The injector employed for these tests is a counter-swirl, radial fuel injector. The fuel is injected into the co-annular air stream in the direction opposite to the swirling air. The model burner and fuel injector are shown in Figure 8.

The model burner was operated at a constant firing rate of 100,000 Btu/hr (30kW) while varying the mixing parameters of swirl intensity and overall combustion air.

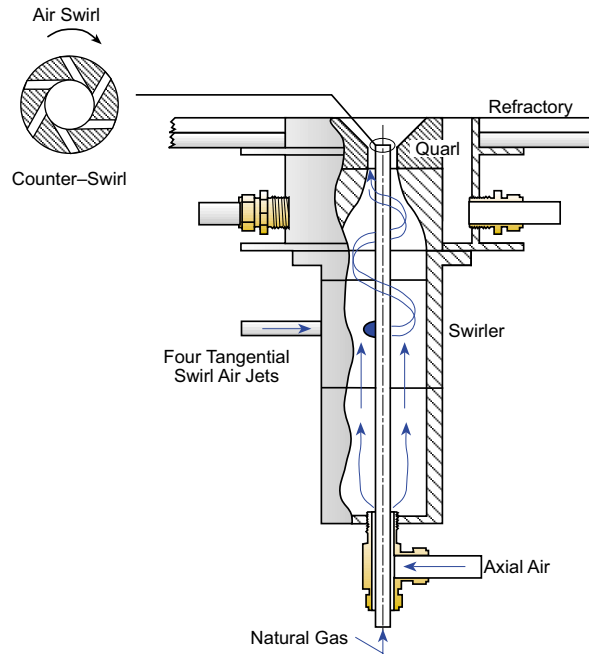


Figure 8: Model Industrial Burner

2.1.2 Commercial Boiler Burner

The scaled-down, industrial boiler burner used in this program was based on a commercially available Coen Company burner, called the Quantum Low NO_x (QLN) burner. The 400,000 Btu/hr (120 kW) scaled-down model was built by Coen and provided to UCI. The burner has three different fuel injection streams (core, radial, and outer) which are used to apply fuel staging for NO_x control. The combustion air is provided via the single air inlet and windbox. The burner schematic is shown in Figure 9.

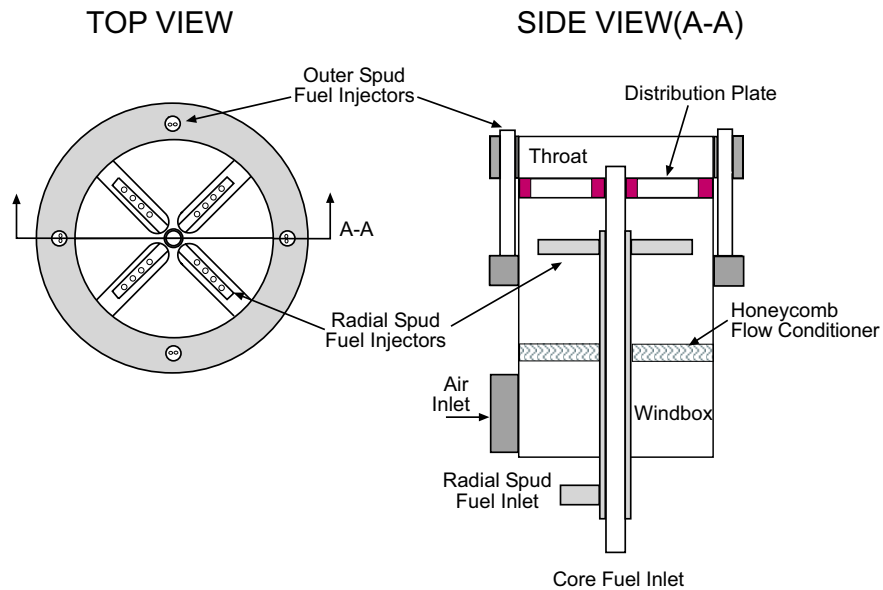


Figure 9: Coen Scaled-Down Commercial Boiler Burner (QLN)

The QLN burner was fired with a core fuel flow equivalent to one quarter of the total firing rate (100,000 Btu/hr). The fuel split to the radial and outer spuds was varied to affect the performance and stability.

2.2 Gas Turbine Combustor Test Stand

Similar to the QLN burner, the gas turbine combustor used for this program has three fuel injection circuits: pilot, wall jets, and centerbody jets. Unlike the QLN, however, which relies on downstream staging for NO_x reduction, the gas turbine combustor utilizes the flexible fuel injection to tailor the fuel distribution in the same plane for NO_x reduction and stability enhancement. The injection strategy adopted utilizes independent circuits to provide control over the distribution of fuel. Radial injection of the fuel into a swirling air flow is employed to provide fast mixing at the injection plane. The pilot fuel is an axial jet provided to add stability, which may be required at low power/startup or in extremely lean regimes. The centerbody fuel injection consists of six individual radial jets injecting into the swirling air annulus. There are

also six wall jets directed radially inward and, for these tests, were oriented directly opposite to the centerbody jets. The combustion air is preheated to 800°F and delivered to a plenum then through a 4-bladed, axial swirler. All of the results presented in this report were conducted at atmospheric pressure. A photograph of the combustor and a close-up schematic of the fuel injection are shown in Figure 10.

Unlike industrial burners, the gas turbine combustor is usually operated at constant air velocity. As such, the air flow was constant and the equivalence ratio and fuel split between the wall jets and centerbody jets was varied to determine their effect on performance.

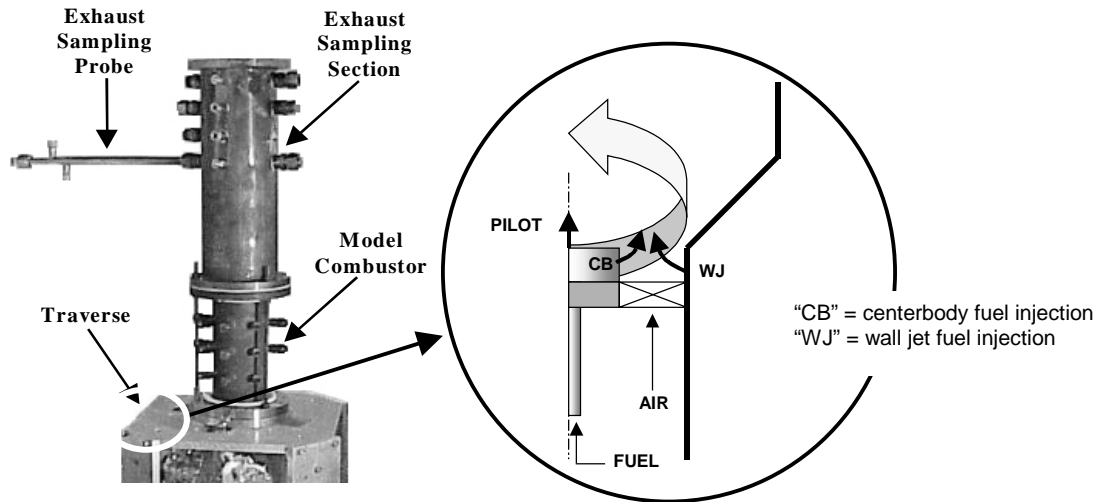


Figure 10: Gas Turbine Combustor with Adaptive Fuel Injection

2.3 Diagnostics

Conventional diagnostics were used to measure the exhaust emissions of the combustion systems. Exhaust emissions measurements were taken using stainless steel, water-cooled sampling probes at the exit of the combustion system, with the sample pumped through a heated Teflon line to a bank of Horiba analyzers. The species measured were carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC), oxygen (O₂), and nitrogen oxides (NO_x). The CO and CO₂ analyzers (Horiba model AIA-220) utilize the non-dispersive infrared technique, the hydrocarbon analyzer is a flame ionization detector, packaged with a paramagnetic oxygen analyzer (Horiba model FIA/PMA-220), and the NO_x analyzer (Horiba model CLA-220) utilizes the chemiluminescence technique. The general emissions sampling schematic is shown in Figure 11.

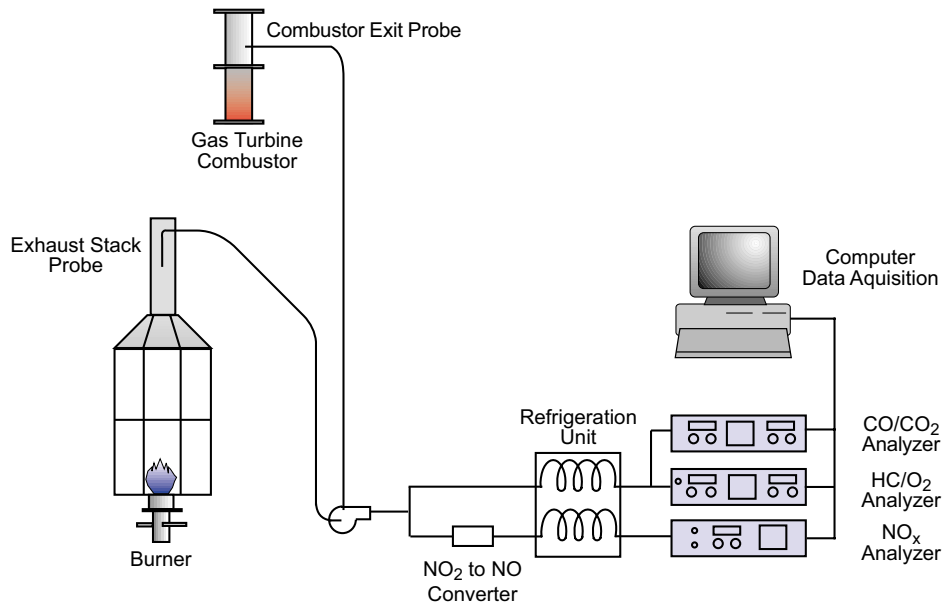


Figure 11: Gaseous Emissions Sampling Schematic

3.0 Results

The project results are presented in terms of the objectives outlined in section 1.1 Goals and Objectives. The work completed toward each objective is described in the following sections.

3.1 Identification of Fast Feedback Sensors

Based on the previous CIEE findings, feedback information is desired on the overall system emissions and performance (“global” values) as well stability indicators (“local” values). The time response of the global feedback through traditional stack emissions measurements could not provide fast response for stability information or “on-the-fly” tuning of the burner system due to the long time required for the gases to travel to the stack, probe, and emissions analyzers. As such, investigation into local or near-flame sensors was initiated. A flow chart of possible sensors and their time response classifications is shown in Figure 12.

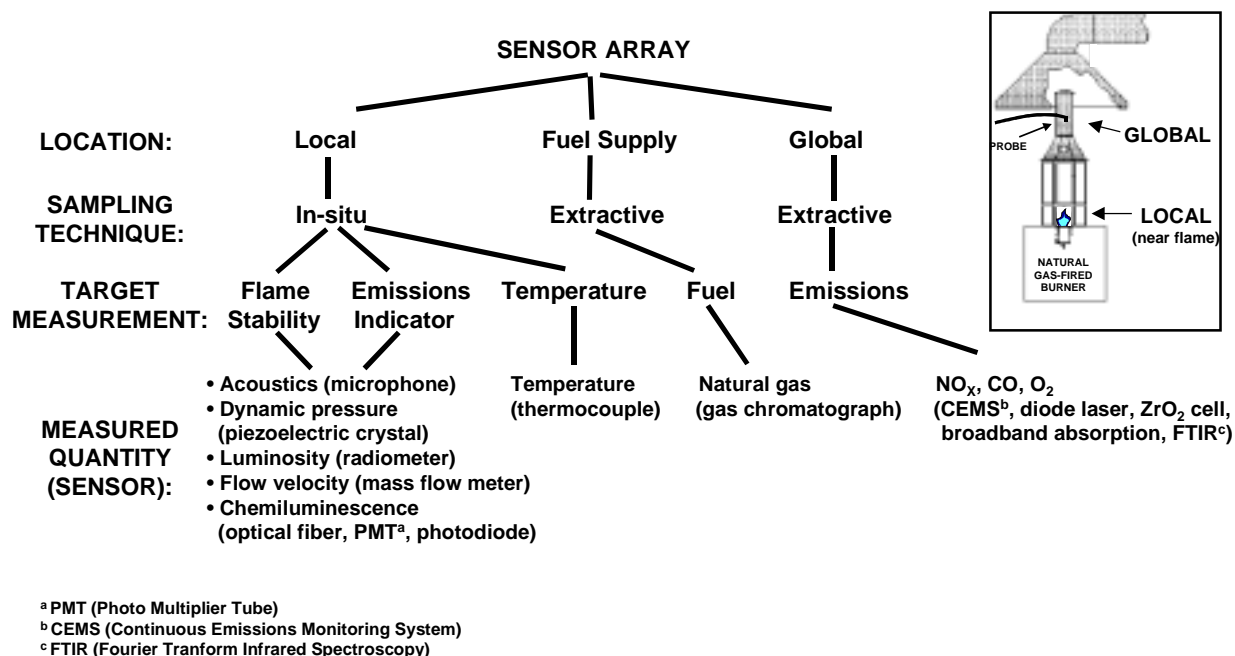


Figure 12: Feedback Sensors Considered

The most appealing sensors are optical or acoustic-based since they provide both fast time response and non-intrusive characteristics. However, many optical techniques require lasers and transmitting/receiving hardware, which can be expensive (greater than \$30,000 for tunable diode lasers) and sensitive to industrial environments. In order to narrow the field, a cost limit of \$5,000 was applied in order to allow investigation of several techniques. The criterion used to select the sensor candidates is listed below:

1. Does the measurement disturb the reaction?
2. Does the technique have a fast time response?
3. Is the instrument easy to use and are the results easy to interpret?

4. Is the instrument robust enough for an industrial environment?
5. Is the cost of the instrument prohibitive?

The three sensor candidate techniques that scored affirmatively on all five characteristics were dynamic pressure fluctuations, combustion acoustics, and flame reaction chemiluminescence. All three techniques are non-intrusive, very fast in time response, easy to understand and setup, and relatively inexpensive (< \$10,000 per experimental system). Furthermore, all three techniques have a history of use as combustion diagnostics. As a result, a dynamic pressure sensor, condenser microphone, and fiber optic collection of chemiluminescence were selected for trials in the industrial burners and gas turbine. The following table provides a summary of the selected sensors' attributes.

Table 3: Selected Sensor Attributes

	Dynamic pressure	Acoustics	Chemiluminescence
Sensor Type	Piezoelectric	Condenser microphone	Fiber optic + PMT
Manufacturer	PCB PiezoTronics	Brühl and Kjær	Fibers: Mitsubishi PMT: Hammamatsu
Model No.	106B50	4145	Fibers: ST-U200D-SY PMT: R106
Time Response (μ s)	≤ 12	≤ 55	≤ 0.024
Sensitivity per input	0.07 mV/Pa	50 mV/Pa	60 mA/W
Max Temperature (°F)	250	150	185
Cost	\$1,300	\$6,000	\$4,000

3.2 Suitability of Selected Sensors

The experimental evaluations of the chemiluminescence, pressure, and acoustic sensors are discussed in the following sections. The dynamic pressure and acoustic measurements are described in the same section since both techniques measure a similar feature of the reaction, the pressure fluctuations caused by the flame (the microphone is essentially a type of pressure transducer).

3.2.1 Chemiluminescence

The yellow-orange emission from radiating carbon particles is a well-known characteristic from rich or diffusion-dominated flames. Due to stringent NO_x emissions regulations, these flames have long since been replaced by better mixed, lean reactions. These leaner, lower temperature reactions are typically blue-green in color due to chemiluminescence from CH and C₂ flame radicals. The hydroxyl radical, OH, and CO₂ molecule are also strong emitters in the ultraviolet. The reaction pathways for these reactions and the wavelengths at which they have the strongest emission are provided below:

Table 4: Chemiluminescence Reactions and Dominant Wavelength Emissions

Reaction	Wavelength (nm)	Spectrum Region
$CH + O_2 \rightarrow CO + OH$	306	ultraviolet
$C_2 + OH \rightarrow CO + CH$	431	visible
$CO + O \rightarrow CO_2$	310- 600	ultraviolet – visible

Numerous studies have been conducted on flame chemiluminescence as an indicator for different reaction characteristics dating back to the 1950's (Samaniego et al., 1995 provides good historical references). The interest in chemiluminescence is high since the measurement is straightforward, non-intrusive, continuous, and intuitively related to the general reaction structure. Since the specified wavelength of light emission is directly related to the number of radicals within the field-of-view, the intensity of the collected signal is proportional to the concentration of the radical species. As a result, studies have tried to empirically relate the chemiluminescence emission to reaction species concentrations, temperature, and heat release.

The intent of this investigation, however, is to relate the radical emissions to performance and stability for use as a fast emissions sensor.

3.3 Approach

In order to determine the ability of flame chemiluminescence or pressure fluctuations to predict stability limits and pollutant emissions, full emissions and operability mappings were conducted on the model industrial burner described previously. Emissions data were collected over the stability range for two different fuel injection geometries: co-swirling fuel and counter-swirling fuel. A schematic of the burner, emissions sampling train, and placement of the fiber optic collection light guides are shown in Figure 13.

One fiber was placed on the outside of the furnace to capture the reaction at the burner exit. The natural 14-degree expansion of the optical fiber was used to encompass the full field-of-view of the reaction. Another fiber was placed at the back-end of the burner, viewing up through the windbox to the burner throat. This location was selected with the intent of capturing the reaction initiation region and simulate the most likely location of a typical, industrial flame scanner. Both fibers collect radical emissions along their line-of-sight, thereby representing integrated radical emissions. The light from the reaction is directed along the fiber to a

collimating lens, two beam splitters, and then through the appropriate filters to photomultiplier tubes (PMTs). Interference filters were used for OH and CH, while a broadband filter was used for CO₂; the wavelengths employed are outlined in Table 4. A schematic of the optical layout is provided in Figure 14. Photographs of the fiber placements and fields-of-view are provided in Figure 15; the red spots are from a HeNe laser directed through the fibers to display the measurement locations. The laser was used for alignment purposes only and represents a useful feature of the fiber optic collection technique; the direction of a laser “backwards” through the fiber allows visual verification of the measurement location and area.

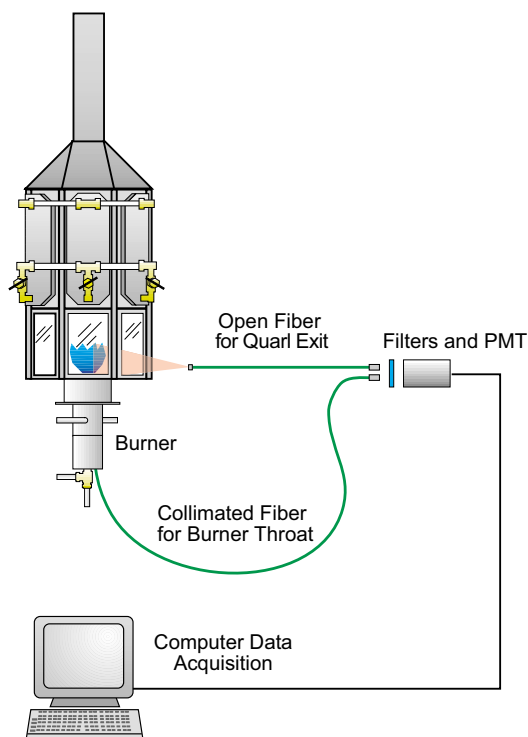


Figure 13: Chemiluminescence Experimental Setup

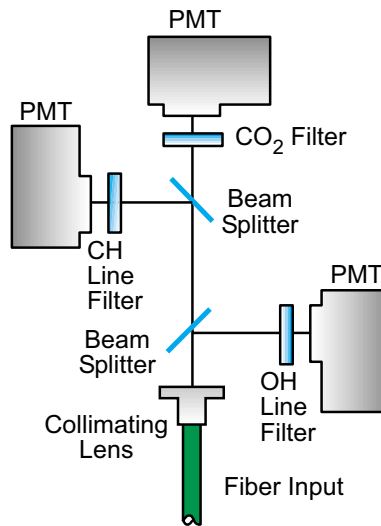
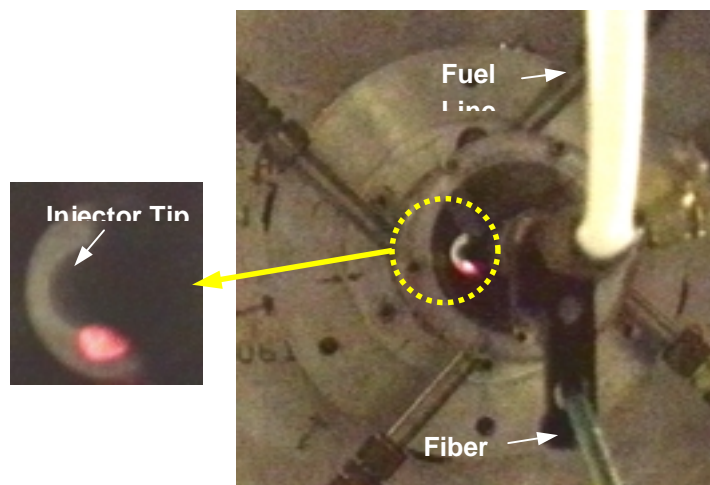


Figure 14: Optical Layout



a) Throat Fiber



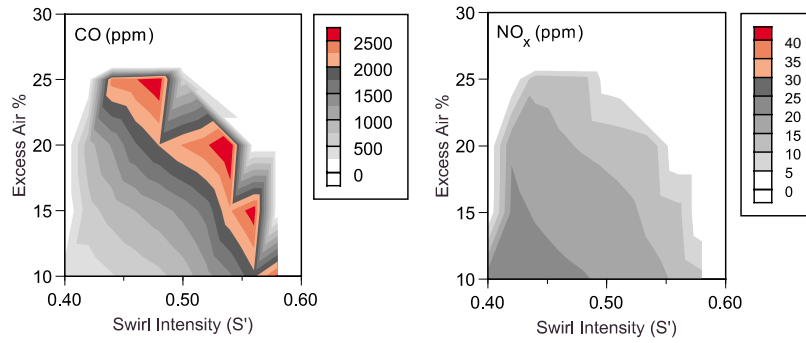
b) Quarl Exit Fiber

Figure 15: Fiber Optic Locations

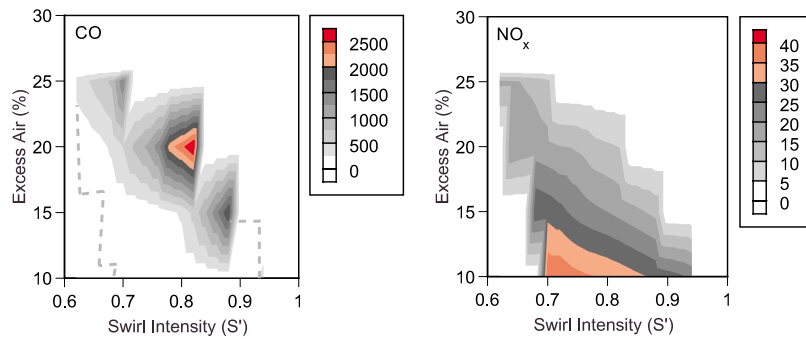
The chemiluminescence data were collected at a sampling rate of 5,000 Hz at a bit resolution of 16,384. This was done to capture the fluctuating component of the time series data. The data were acquired and processed using *LabView* programming software. Six runs of data ($6 \times 16,384$) were processed to arrive at the average and fluctuating values per condition; this number of runs was selected based on (1) initial measurements of repeatability, (2) computer processor capability, and (3) experimental expedience.

3.4 Results

NO_x and CO emissions maps for the two different injectors are shown in Figure 16 in terms of swirl intensity (S') and excess air. The different emissions characteristics are known from previous studies, with the co-swirl injector displaying low NO_x but much higher CO emissions. These two sets of emissions maps provide a good example of the NO_x -CO trade-off inherent in combustion systems.



a) Co-swirl Injector CO and NO_x Emissions



b) Counter-swirl Injector CO and NO_x Emissions

Figure 16: Co-swirl and Counter-swirl Injector Emissions

Chemiluminescence measurements of OH, CH, and CO_2 were taken concurrently with the emissions data. In order to illustrate the magnitudes of the emissions, scatter plots are shown in

Figure 17 with the OH, CH, and CO₂ emissions (throat) at 10% excess air for both the co-swirl and counter-swirl injectors. The magnitudes of the signals represent nano-amperes and were not processed to provide actual concentrations, hence the “arbitrary units”. The main intent of these plots is to illustrate the relative signal strength of the different species for both injectors. The profiles appear to follow the same trends for both injectors, with CO₂ providing the highest intensity levels as expected. In order to gain the largest dynamic range and to conserve space, only the OH and CO₂ results are presented in subsequent diagrams (the CH data, although lower in intensity, show similar trends as the OH values).

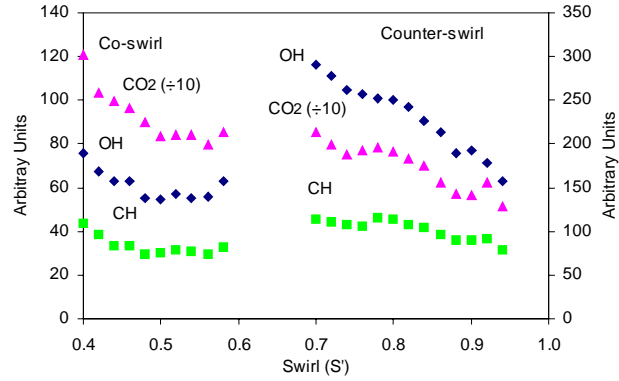
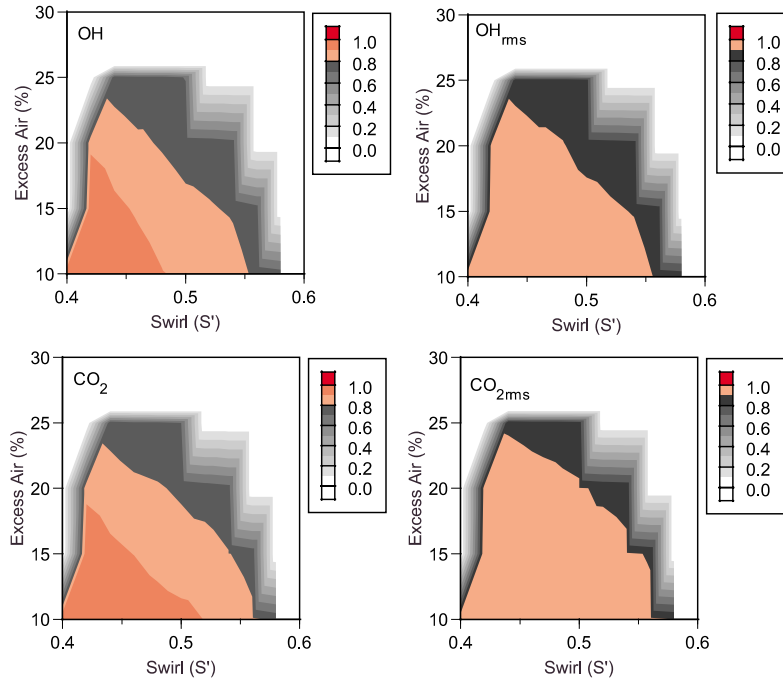
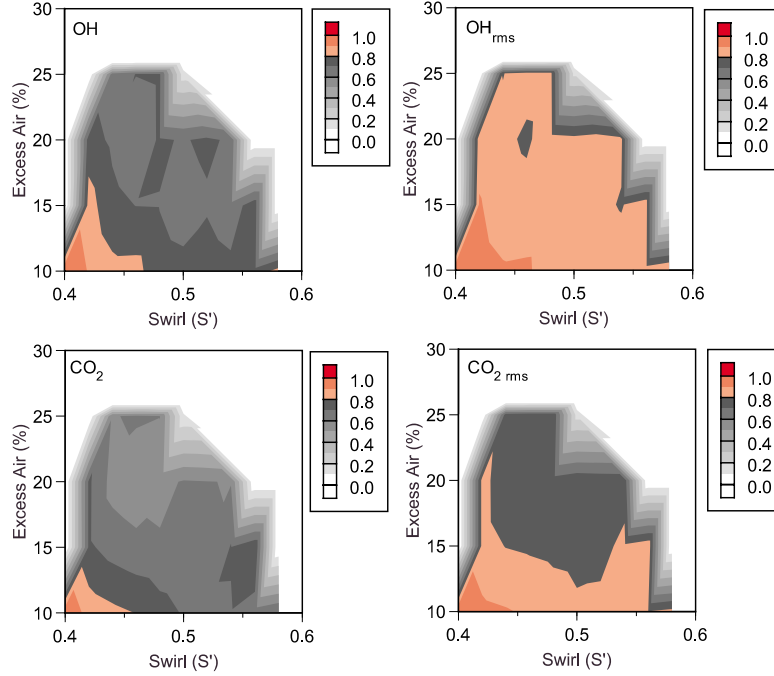


Figure 17: Chemiluminescence Profiles at 10% Excess Air

In order to examine the chemiluminescence trends more closely, the data were normalized and plotted in a similar fashion to the emissions data. The average and fluctuating component values for OH and CO₂ are shown for the co-swirl injector in Figure 18 for both the quarl exit and throat locations.



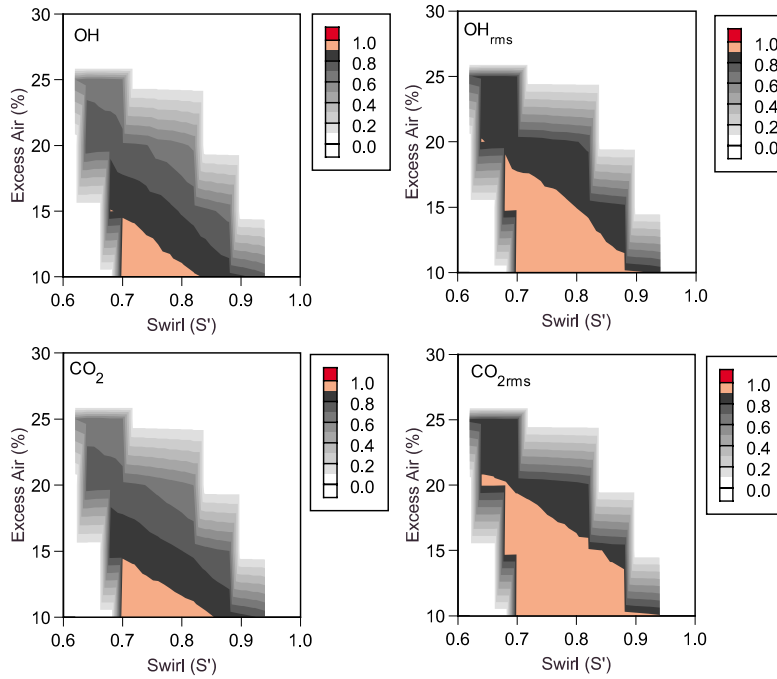
a) Quarl Exit



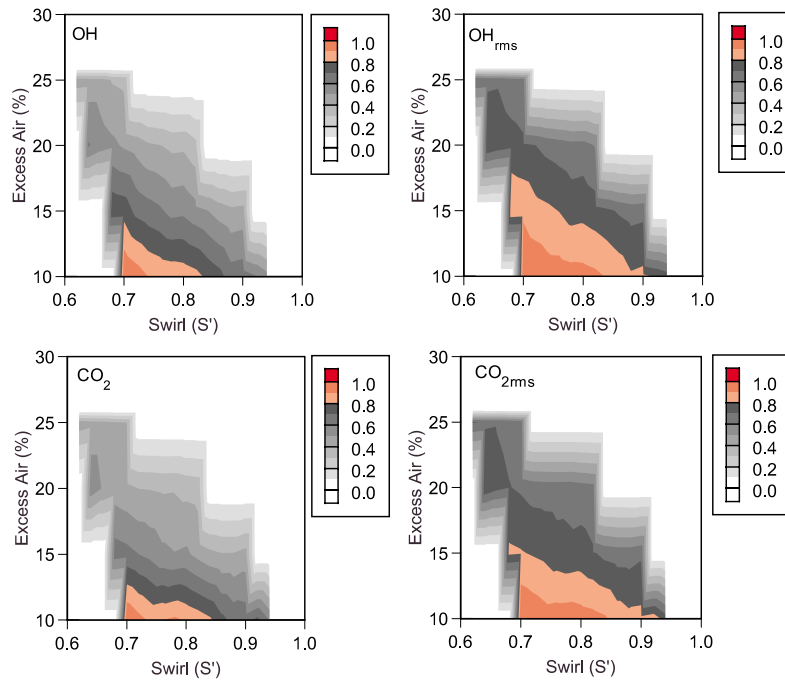
b) Throat

Figure 18: OH and CO₂ Average and Fluctuating Chemiluminescence for the Co-swirl Injector

Similar plots for the counter-swirl injector are presented in Figure 19, which also shows high correlation to the average NO_x emissions.



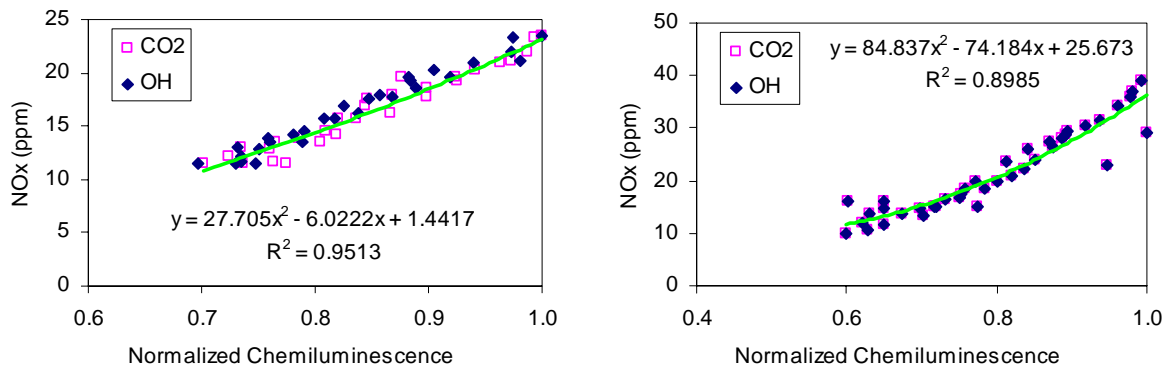
a) Quarl Exit



b) Throat

Figure 19: OH and CO₂ Average and Fluctuating Chemiluminescence for the Counter-swirl Injector

These plots display similar contours of high average chemiluminescence signals in regions of operation where NO_x emissions are also high. This is shown directly by plotting the NO_x vs. the average OH and CO₂ chemiluminescence signals for both injectors in Figure 20. The high correlation coefficients are also shown on the plots.



a) Co-swirl Injector

b) Counter-swirl Injector

Figure 20: Chemiluminescence Correlation to NO_x Emissions

Based on these results, the average chemiluminescence signals of either OH or CO₂ can be used as a close estimator of NO_x emissions to provide faster feedback response.

From the previous chemiluminescence figures, however, there was no clear correlation to CO emissions. It was expected that a fluctuating component of some radical species would provide an indication of global CO emission. This was based on the hypothesis that poor mixing or quenching would cause intermittent heat release (radical formation). This was not borne out by the measurements. Upon further reflection, however, it was recognized that (1) the measurements represent a spatial average of species and (2) the chemiluminescence signals decreases with increasing strain (i.e., conditions of potential increases in exhaust CO). In order to adjust for these considerations, the fluctuating components were normalized by the average values to provide a percent fluctuation level. These plots are provided in Figure 21 for the co-swirl injector and Figure 22 for the counter-swirl injector at both fiber locations.

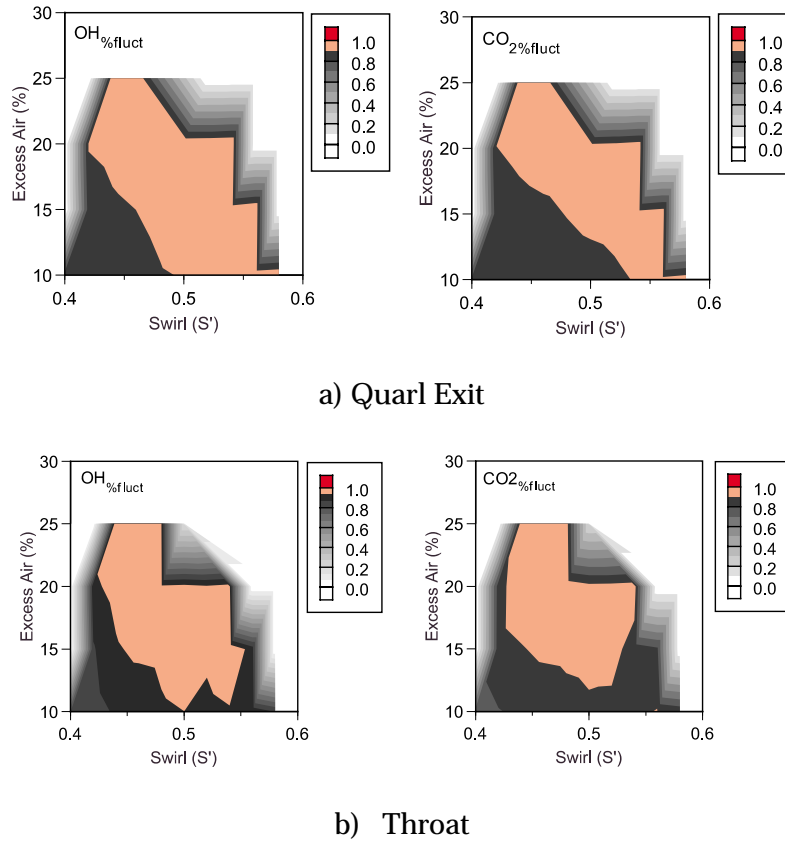
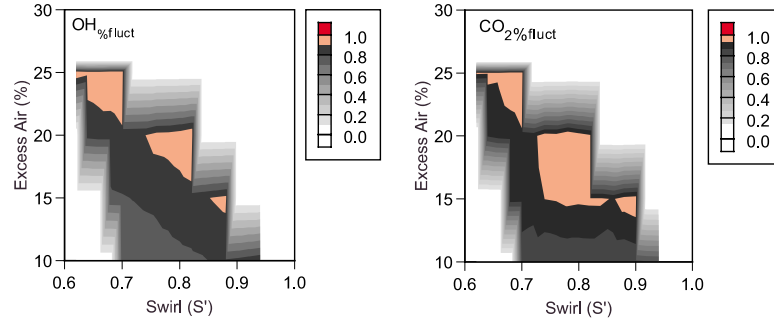
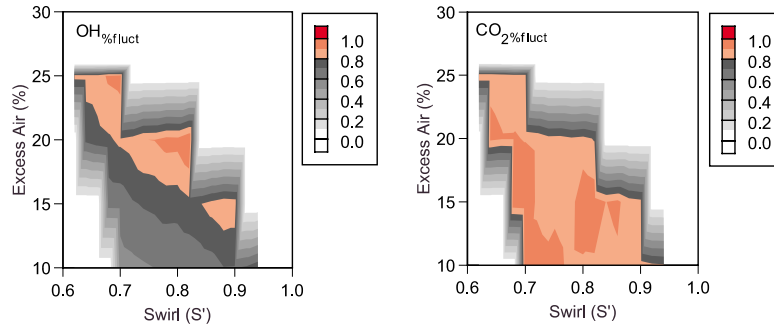


Figure 21: OH and CO₂ % Fluctuations for Co-swirl Injector



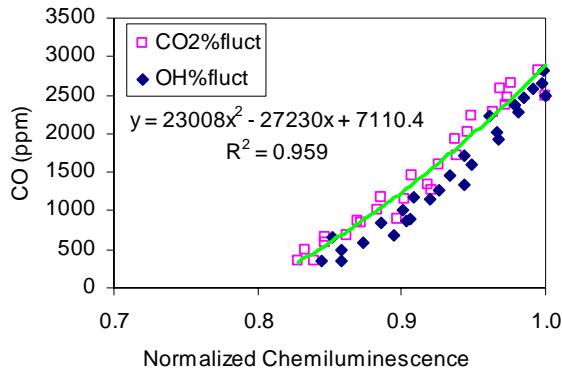
a) Quarl Exit



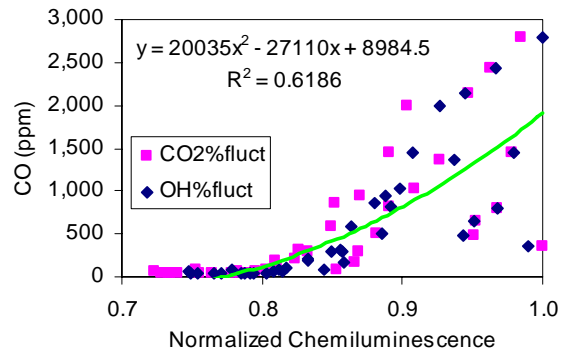
b) Throat

Figure 22: OH and CO₂ % Fluctuations for Counter-swirl Injector

The percent fluctuation of the chemiluminescence signals seems to show a correlation to the regions of high CO emission. This is plotted directly in Figure 23 for the OH and CO₂ signals for the open fiber; although the trend is apparent, there are more excursions from the fit than shown for the NO_x correlation. Despite these outliers, the correlations fit well enough to provide an estimator of CO emissions for the fast feedback.



a) Co-swirl Injector



b) Counter-swirl Injector

Figure 23: Chemiluminescence Correlation to CO Emissions

3.4.1 Dynamic Pressure Sensor and Acoustic Microphone

Pressure fluctuations and acoustic signals have long been related to the combustion reaction and heat release. As such, a PCB Piezotronics dynamic pressure sensor (model 106B50) and Brüel and Kjær microphone (model 4145) were evaluated as fast feedback sensors. The dynamic pressure sensor was placed on the furnace wall adjacent to the burner quartz exit, and the microphone was placed outside the furnace at a distance away from the window as shown in Figure 24.

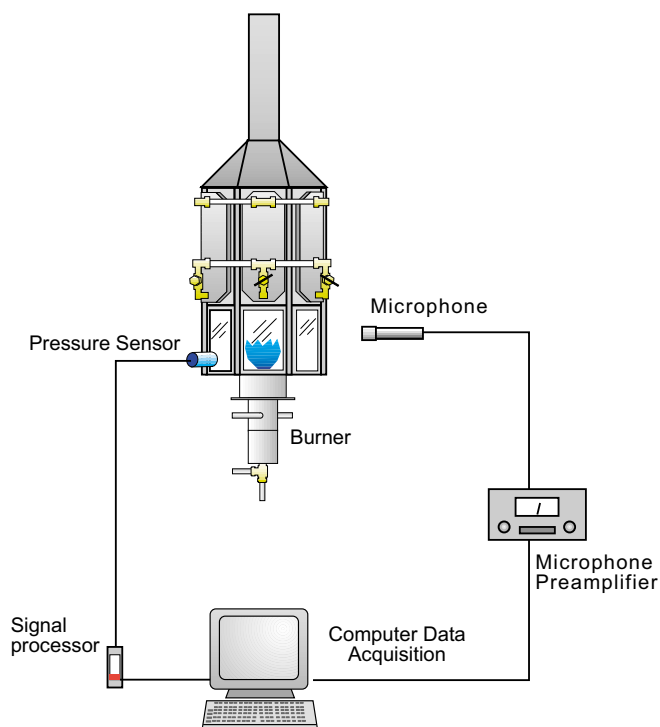


Figure 24: Placement of Dynamic Pressure Sensor and Microphone

The signals from the two sensors were evaluated over the entire operating range of the model burner for the counter-swirl and co-swirl injectors. The fast Fourier transformed (frequency trace) signals were analyzed for correlations to stability, NO_x emission, and CO emission. An example of the frequency plots is shown in Figure 25.

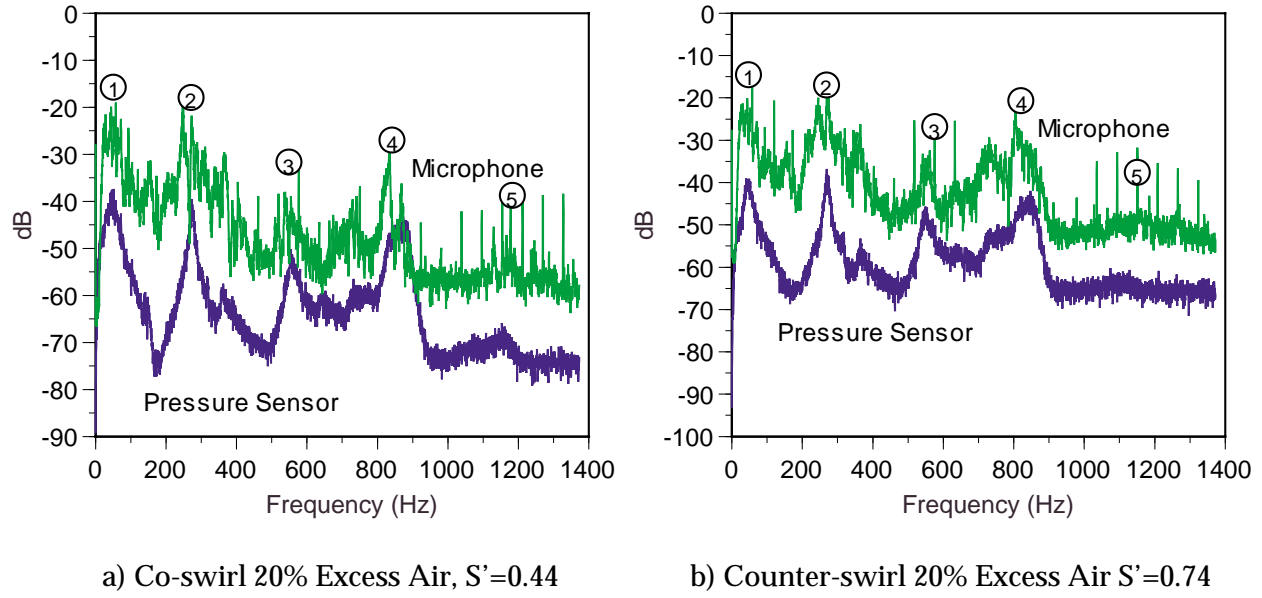


Figure 25: Frequency Response of Model Industrial Burner

Five distinct frequency ranges where peaks consistently occurred were identified near 50, 270, 550, 850, and 1100 Hz as shown in Figure 25 as circled numbers. Within ranges of these peaks, the average and rms for the peak power and frequency at which the peak power occurred were analyzed in a similar manner as the chemiluminescence data. Representative examples of the average and rms peak frequency contour plots are shown in Figure 26 for the counter-swirl injector.

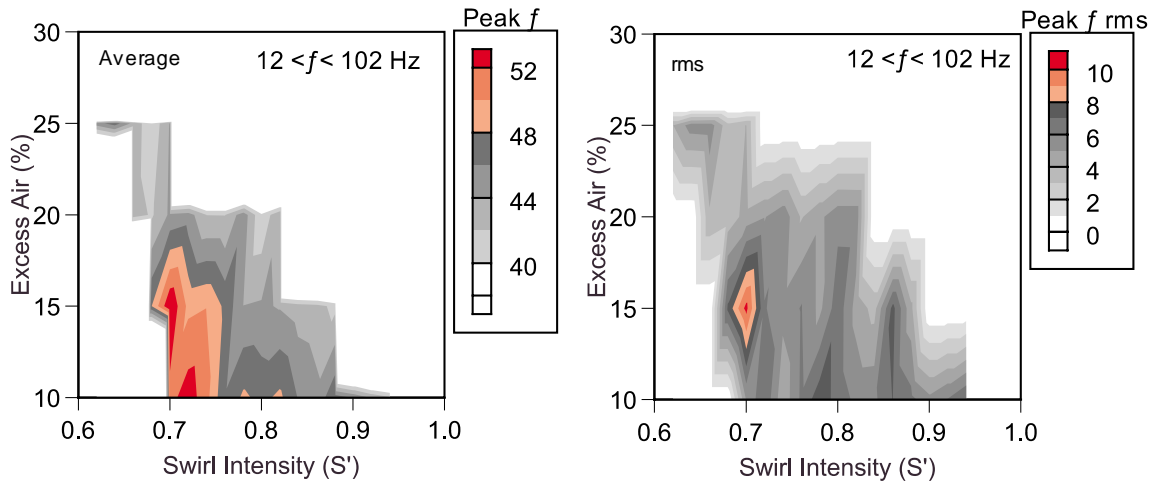


Figure 26: Peak Frequency Response between 12 and 102 Hz for Counter-swirl Injector

This plot shows the average peak frequency was 52 Hz near the low swirl stability and the frequency fluctuated by 10 Hz in this same region (indicated by red color in both plots). Unfortunately, there were no general trends identified that could serve as estimators for NO_x .

CO, or stability. This result was not surprising due to the relatively large chamber volume in relation to the reaction volume. As such, the pressure sensor and microphone were not used for the industrial burner active control feedback. The microphone, however, was re-evaluated for the gas turbine combustor active control tests (see section 3.7 SGAC Demonstration on Gas Turbine Combustor).

It should be noted that despite the poor correlations for the dynamic pressure sensor and microphone in the industrial burner, further research is warranted before completely discounting these sensors. Several other tests are being planned to make the measurements more localized and less dependent on the furnace volume (i.e., placement of the sensors closer to or within the burner).

3.5 Upgrade of Active Control Software

A second-generation active control (SGAC) program was developed using state-of-the-art software tools. The previous active control program (St. John and Samuelsen, 1994) was written in *Visual Basic*. Although this program worked very well and incorporated a user-friendly interface, the programming and data acquisition were difficult to modify or incorporate new search algorithms. For the SGAC program, a modular approach was adopted using *LabView* as the data acquisition engine and different software packages to code the algorithms. A schematic of the SGAC concept is shown in Figure 27.

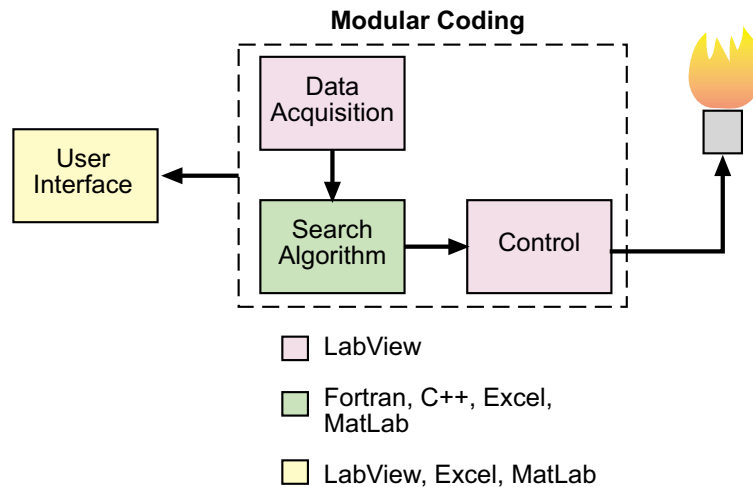


Figure 27: Second Generation Active Control Concept

The active control program modules consist of three parts: data acquisition, algorithm, and control; the dashed line in Figure 27 represents components that will be transparent to the user in the completed version. The data acquisition and control aspects were handled by *LabView* and National Instruments data acquisition cards. This allowed for easier portability and consistency from one combustion system to the next. The actual control layout is shown schematically in Figure 28.

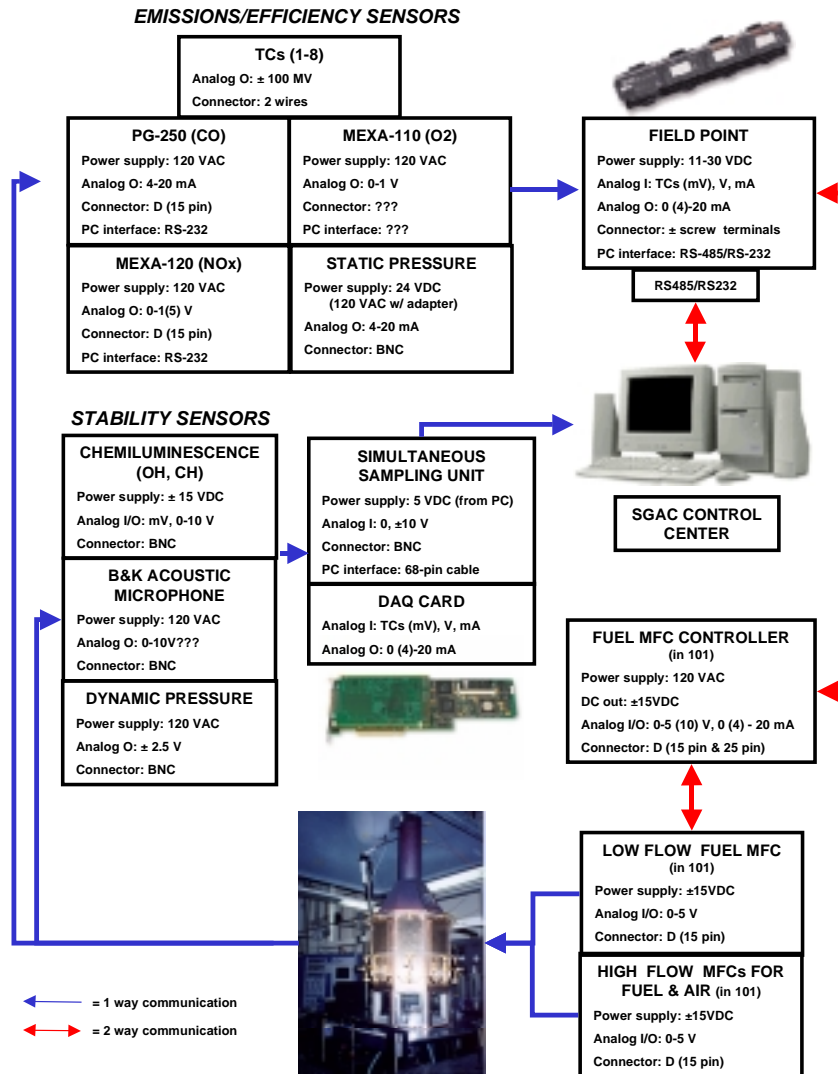


Figure 28: SGAC System Schematic

The control algorithm was coded using *Fortran* (for the industrial burners) and *Visual Basic* in Excel (for the gas turbine). The different coding methods were done to evaluate the ease-of-use and data exchange rates for the algorithm module. Both codes, however, used the direction-set, or Powell's method, of optimization. This optimization strategy simply looks in a prescribed direction for a maximum value of performance. If the new value is higher, then the system continues in that direction; if the new value is lower, the system returns to the previous point and initiates a search in a new direction.

A challenge associated with this simple technique is that the prescribed direction and step size are often times inadequate for all conditions and can optimize on local peaks. An algorithm which can adjust and learn from previous runs would be useful (fuzzy logic). The next steps for this research will include the comparison of different optimization techniques and incorporation of a "learning" mode to minimize the time for optimization.

3.6 SGAC Demonstration on Industrial Burners

3.6.1 Model Burner

The initial tests of the integrated SGAC system were conducted on the model industrial burner. The first task was to conduct an emissions mapping of the entire burner operational “space” in order to know *a priori* where the performance peaks occur (this was required to ensure the SGAC optimized in the correct location but will not be necessary for the commercial technology). The NO_x and CO emissions data were then inserted into the performance function to calculate the performance index, J , at each location.

$$J = w \cdot f(NO_x) + w \cdot g(\eta)$$

The performance plots are provided as contour maps for all of the subsequent active control optimization runs, with red and orange colors indicating high performance (low NO_x and CO) and green and blue colors indicating poor performance (high NO_x or high CO). The model burner performance map is shown in Figure 29.

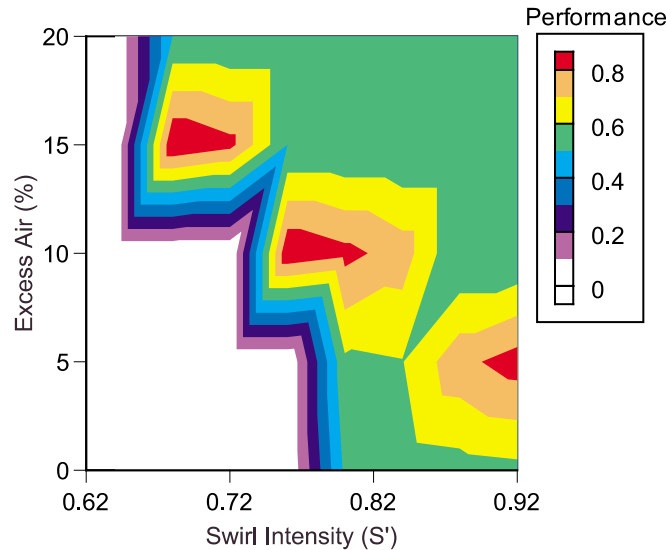


Figure 29: Model Burner Performance Map

The baseline feedback sensors were the exhaust NO_x and CO emissions analyzers. Although slow in response time, these data are consistent with a continuous emissions monitoring system (CEMS) used in industry. The approach for these tests occurred as follows:

1. Map performance using emissions analyzers over the entire stability limits to establish the “good” and “bad” regions (for experimental purposes only)
2. Conduct SGAC using emissions analyzers to establish a baseline response
3. Repeat SGAC using fast sensors
4. Compare SGAC results

The baseline optimization using the emissions analyzers as feedback is shown in Figure 30. The black lines indicate the search path and the circled numbers indicate the start ① and finish ②. The search optimization time using the SGAC and exhaust emissions is 14 minutes. The long optimization time is a function of the (1) time required for the system to reach steady state prior to a measurement and (2) the actual measurement (sampling) time. Due to the large volume of the chamber, the low burner firing rate, and the long time required for an average exhaust stream sample, the overall system response time is slow (approximately 1 minute). A similar test was conducted using the OH chemiluminescence as the feedback sensor and NO_x and CO correlations for performance estimation (see Figure 20 and Figure 23). Since the OH chemiluminescence is an optical measurement, the system response time is much lower due to the much faster sampling capability. However, the system settling time (i.e., time required to reach steady state after changing conditions) remained the same. The search history and performance map are shown in Figure 31.

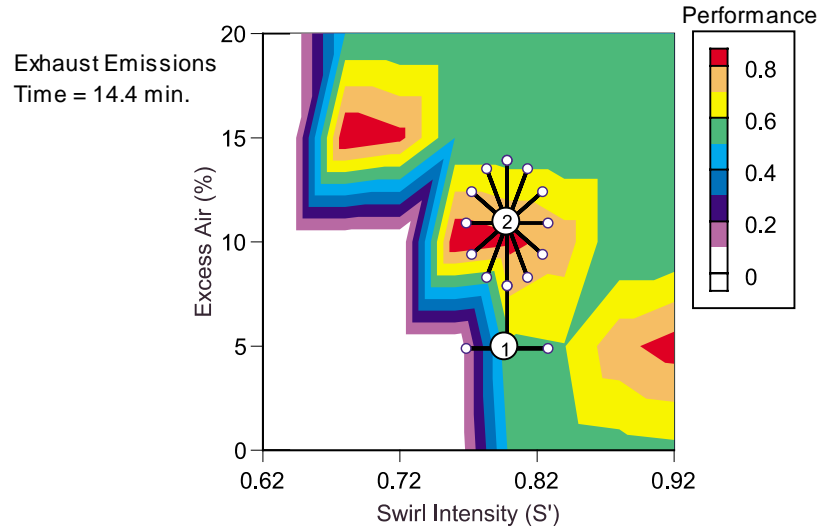


Figure 30: SGAC for Model Burner with Exhaust Emissions Sensor
[① start, ② finish]

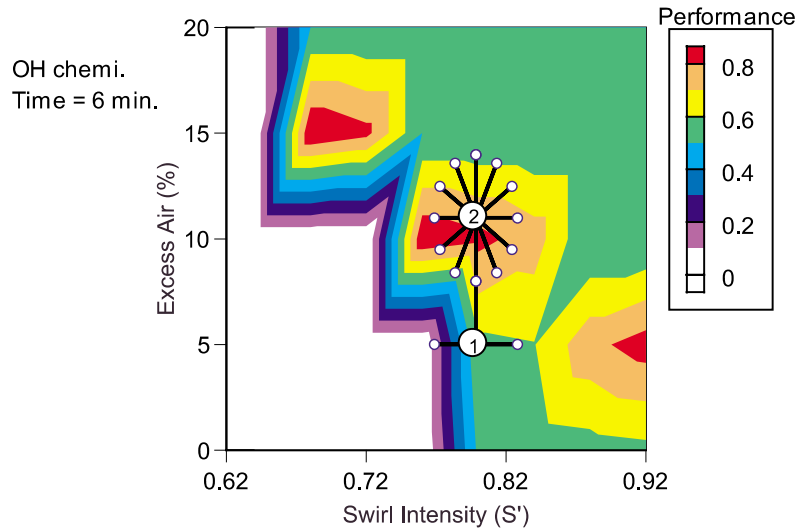


Figure 31: SGAC for Model Burner with Chemiluminescence Sensor
[① start, ② finish]

The search history using the OH chemiluminescence is the same as with the slower emissions feedback, but the optimization time is 2.4 times faster. A caveat using the optical sensor for the feedback with performance estimation is that the optimization can only be as accurate as the NO_x and CO correlations. As a result of data scatter on the correlation plots, optimization using estimation may be slightly different than when using the actual emissions.

Other trials were also conducted using different parameters (e.g., starting points) in order to fine-tune the software settings. All trials had similar results, with both feedback sensors optimizing to peaks on the performance maps. As stated previously, however, the direction-set algorithm is subject to settling on local peaks. This feature was evidenced in our results and will be addressed in future algorithm development.

In order to test the SGAC on a more industrial system, the Coen QLN scaled-down boiler burner was used to conduct similar trials using the exhaust emissions analyzers and OH chemiluminescence as feedback sensors.

3.6.2 Boiler Burner

Like the model burner tests, the exhaust emissions analyzers were used as the feedback sensor for the initial QLN boiler burner trials. As shown in Figure 9, the QLN has three fuel streams: core, radial, and outer. The core fuel was set at 25% of the total firing rate, and the remaining fuel was varied between the radial and outer spuds. The remaining fuel was defined as

$$fuel\ split = outer\% - radial\%$$

For example, if all of the remaining fuel is diverted to the outer spuds, this was considered “75% fuel split,” or more staging. Conversely, if all of the remaining fuel is diverted to the radial spuds, this was considered “-75% fuel split,” or more premixed. The performance map for the QLN burner is shown in Figure 32. These results indicate a ridge of high performance along the stability limit (represented by the red color).

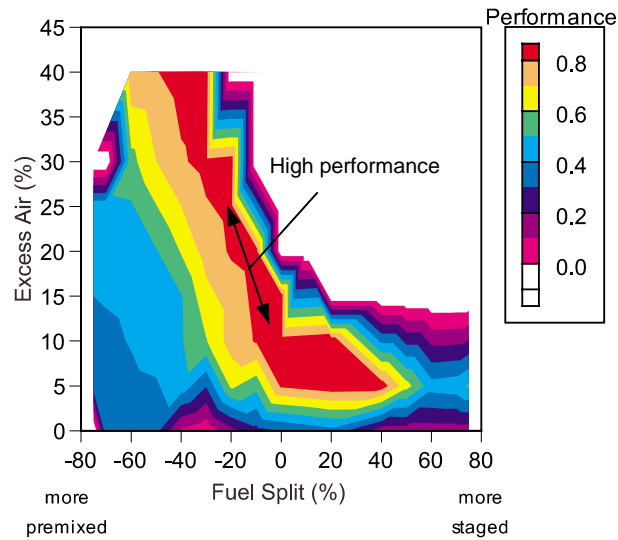


Figure 32: Boiler Burner Performance Map

Following the same approach previously adopted for the model burner, the baseline optimization tests were conducted using the exhaust emissions analyzers. The resulting operational history is provided in Figure 33.

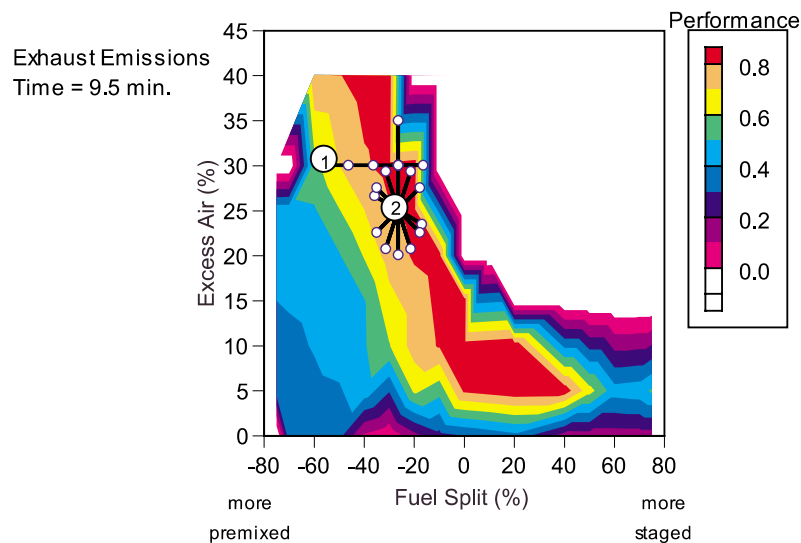


Figure 33: SGAC for Scaled-Down Boiler Burner with Exhaust Emissions Sensor
[① start, ② finish]

The SGAC successfully optimized to the ridge of high performance located at 25% excess air after 9.5 minutes. This plot, however, exemplifies a limitation of the original performance function based on NO_x and CO emissions; specifically that system efficiency is ignored so higher excess air values are not penalized. A modified performance function was developed to incorporate the stack $\text{O}_2\%$, which can be related to system efficiency (Thompson, Shiimoto, and Muzio, 1999).

$$J = w \cdot f(\text{NO}_x) + w \cdot g(\eta) + w \cdot h(\text{O}_2)$$

For these tests, each function was weighted evenly at 1/3 and the function $h(\text{O}_2)$ was linearly increasing with decreasing stack O_2 . After incorporating this system efficiency modification, the peak is no longer located at high excess air values and actually relocates to 5-10% excess air and 0-30% fuel split. The map for this performance definition is shown in Figure 34.

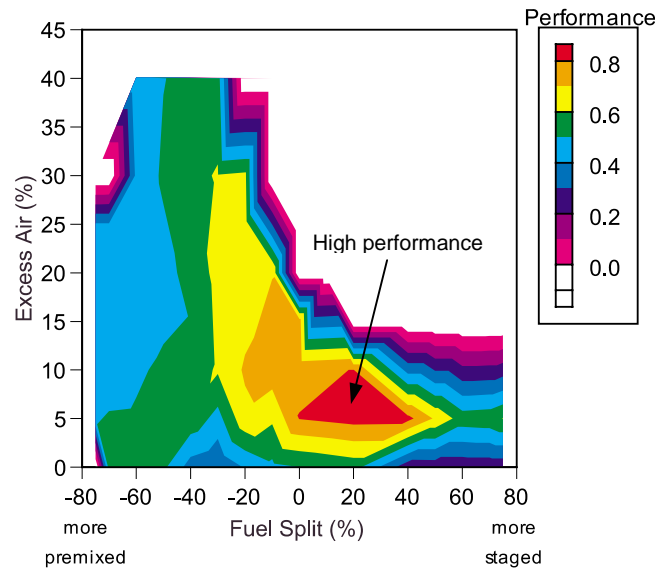


Figure 34: Boiler Burner Performance Map with System Efficiency Factor

The optimization was repeated using this performance definition and the exhaust emissions analyzers for feedback. The SGAC successfully optimized in the region of high performance, at lower excess air and more fuel staging, with a response time of 16 minutes. The optimization history is shown in Figure 35.

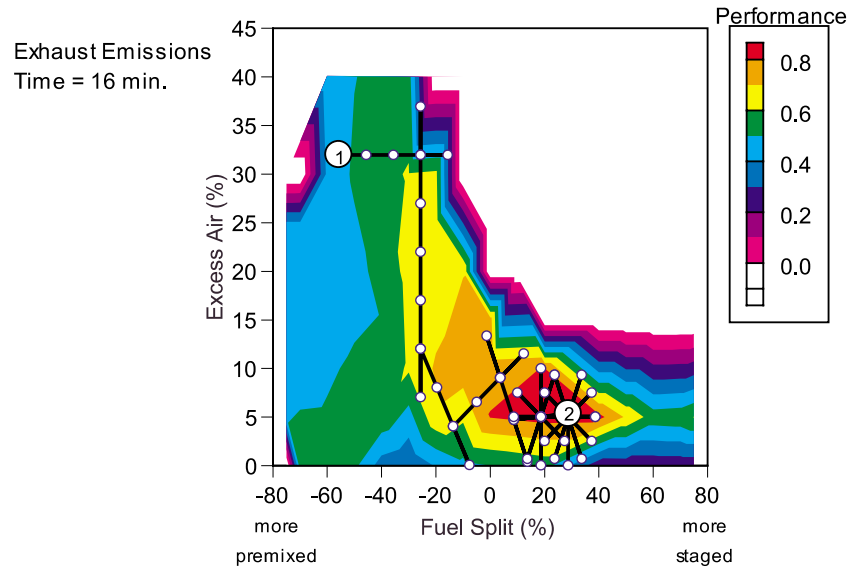


Figure 35: SGAC for Scaled-Down Boiler Burner with Exhaust Emissions Sensor and System Efficiency Factor
[① start, ② finish]

The faster feedback chemiluminescence sensor was next incorporated into the SGAC system to compare the response time. The optimization history is overlaid on the performance map in Figure 36.

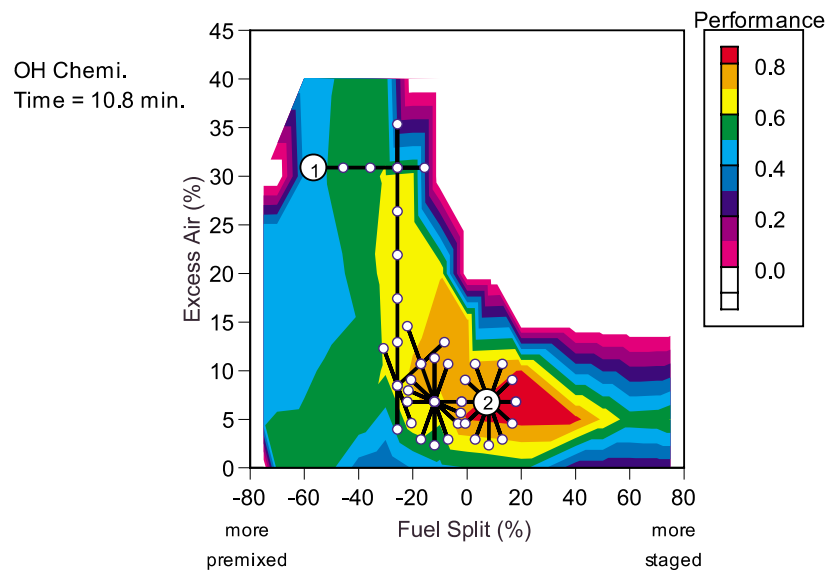


Figure 36: SGAC for Scaled-Down Boiler Burner with Chemiluminescence Sensor and System Efficiency Factor
[① start, ② finish]

The fast sensor SGAC system successfully optimized operation in the same peak region as with the emissions analyzers, but with a 1.5 times faster time response. Although the SGAC did not arrive at the exact same location as the emissions analyzers feedback trial, it did optimize on the same peak. This slight discrepancy may be due to

1. The use of correlations for NO_x and CO such that the peak performance is slightly different for the chemiluminescence sensor and the emissions analyzers,
2. Slight changes in the performance value during sampling (all of the values in the peak region are within 0.015),
3. The step-size selected for each iterative search may have been too small and “missed” the peak, or
4. Any combination of the above.

With this experience, the SGAC was next targeted for implementation on the gas turbine combustor firing on natural gas.

3.7 SGAC Demonstration on Gas Turbine Combustor

3.7.1 Fast Feedback Sensors Development

To provide fast feedback for the gas turbine active control, two of the previous sensors were investigated: chemiluminescence and acoustics. The gas turbine was outfitted with a quartz liner in order to observe the reaction. The fiber optic light guide was positioned to capture a full field-of-view of the reaction, and the microphone was placed at the combustor exhaust. A schematic of the setup and a photograph of the reaction and quartz liner are shown in Figure 37.

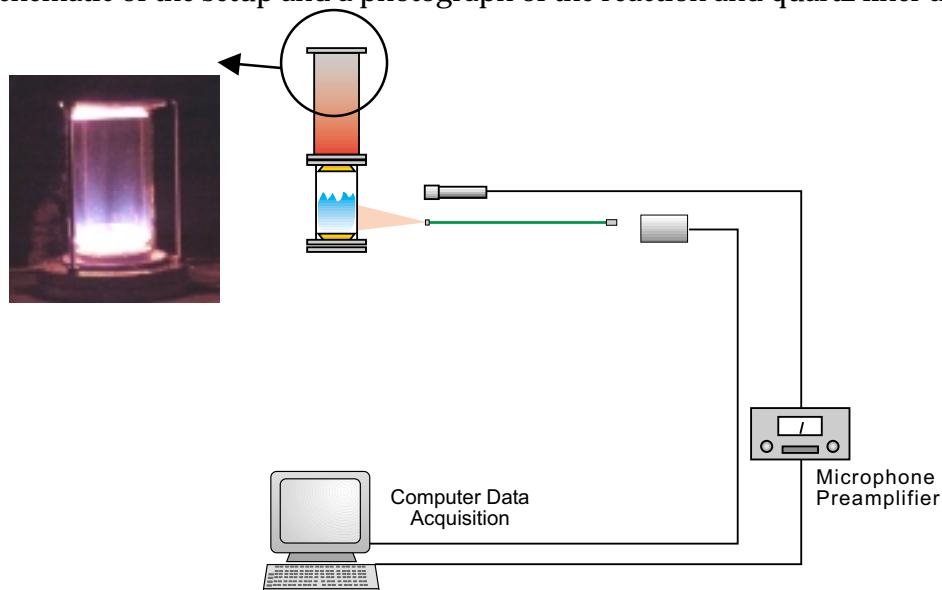


Figure 37: Fiber Optic and Microphone Placement for Gas Turbine

The gas turbine combustor has two fuel streams, radial out from a centerbody and radial in from wall jets (see Figure 10). The fuel split was varied to provide different degrees of mixing

and the overall fuel flow rate was varied to provide different equivalence ratios. Exhaust emissions, chemiluminescence, and acoustic signals were taken simultaneously to obtain contour maps of the gas turbine operational space in terms of equivalence ratio and centerbody fuel split. The exhaust emissions maps for the gas turbine combustor are shown in Figure 38. The NO_x and CO emissions are relatively insensitive to changes in the fuel split (% Centerbody) but show large gradients with equivalence ratio.

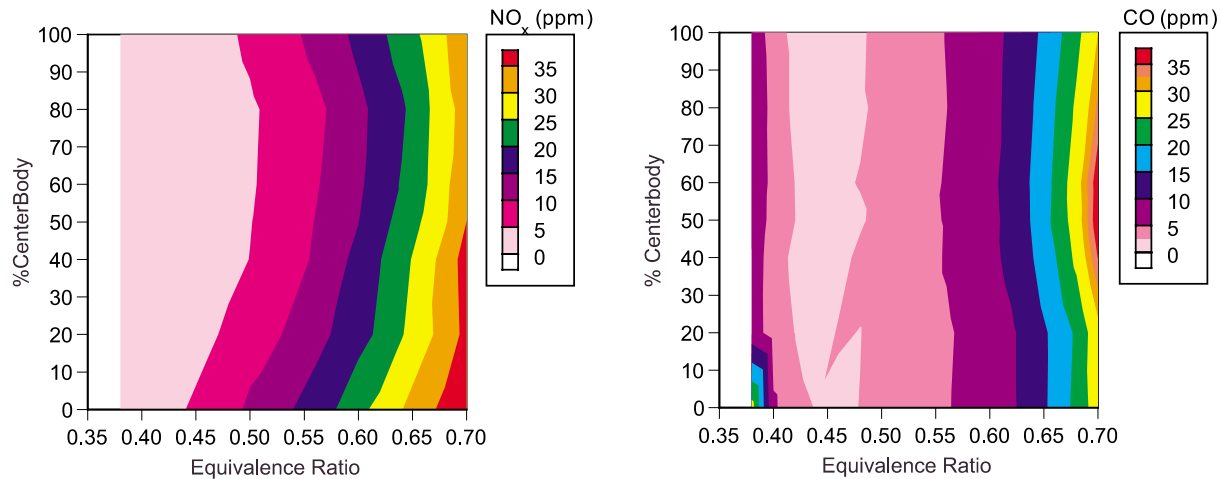


Figure 38: Gas Turbine Combustor Exhaust Emissions

These emissions values are combined into the performance function in Figure 39; the black dot at 80% centerbody and 0.42 equivalence ratio represents the maximum condition. It should be noted, however, that all of the conditions between 0.42 and 0.44 equivalence ratio represent a “ridge” of high performance, differing only in a few percent.

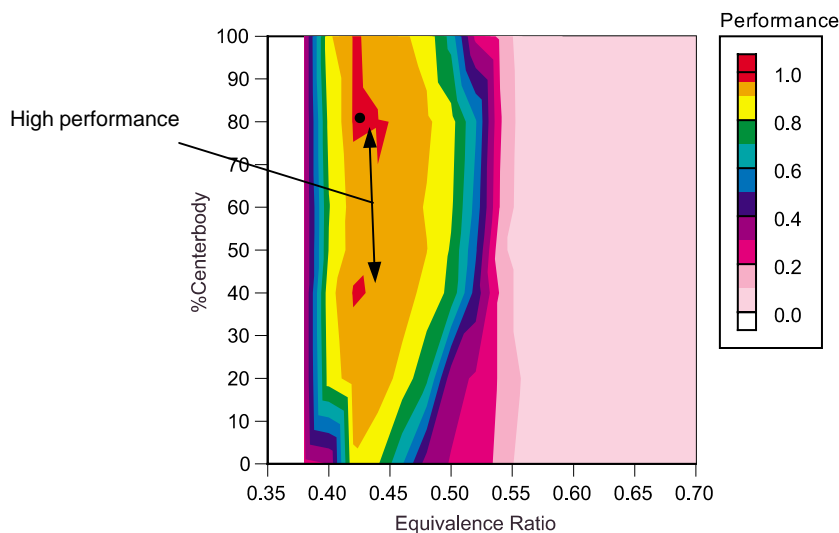
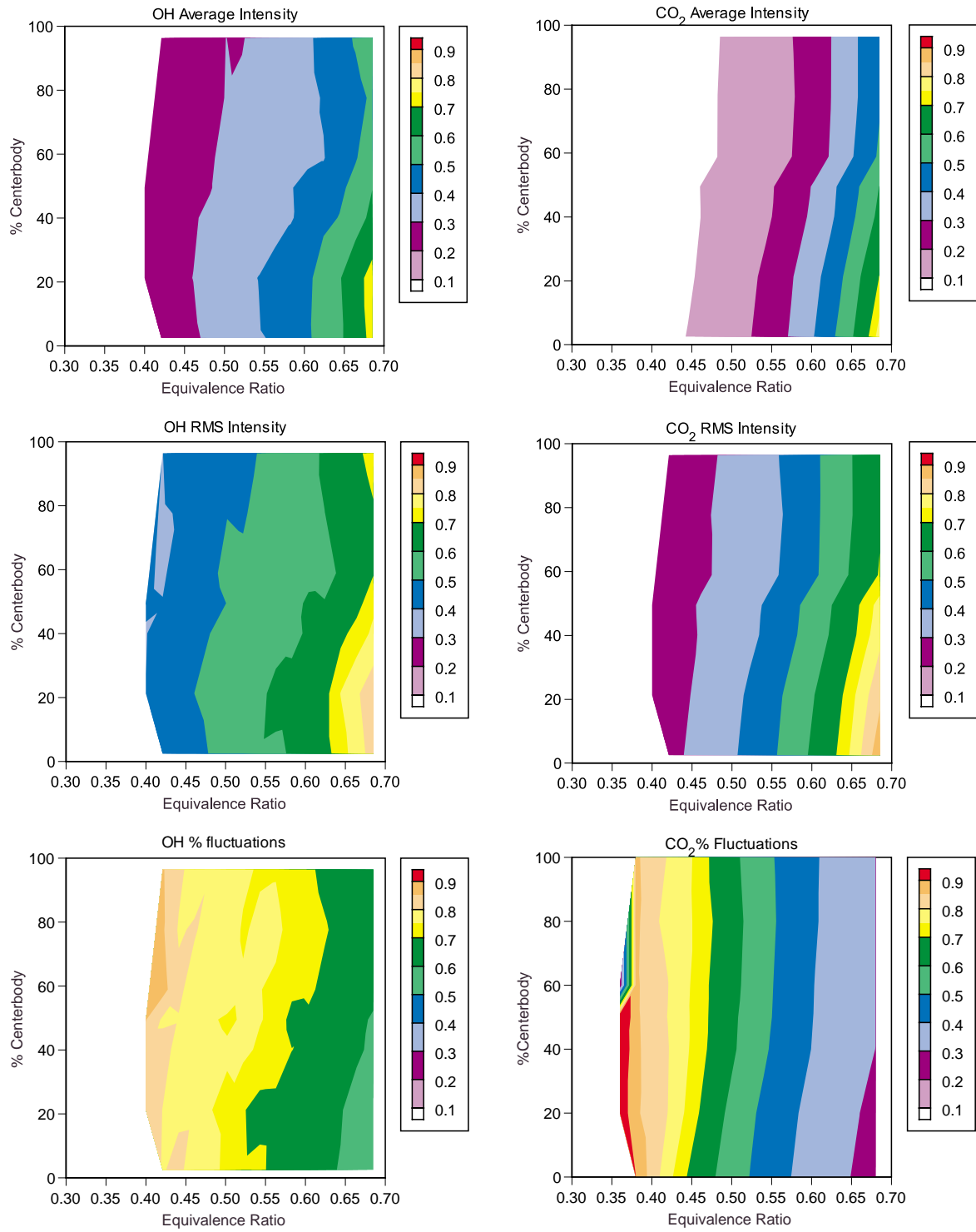


Figure 39: Gas Turbine Combustor Performance

In order to determine the relation of chemiluminescence to these exhaust gas emissions, the normalized OH and CO₂ average, rms, and percent fluctuation values are plotted in Figure 40.

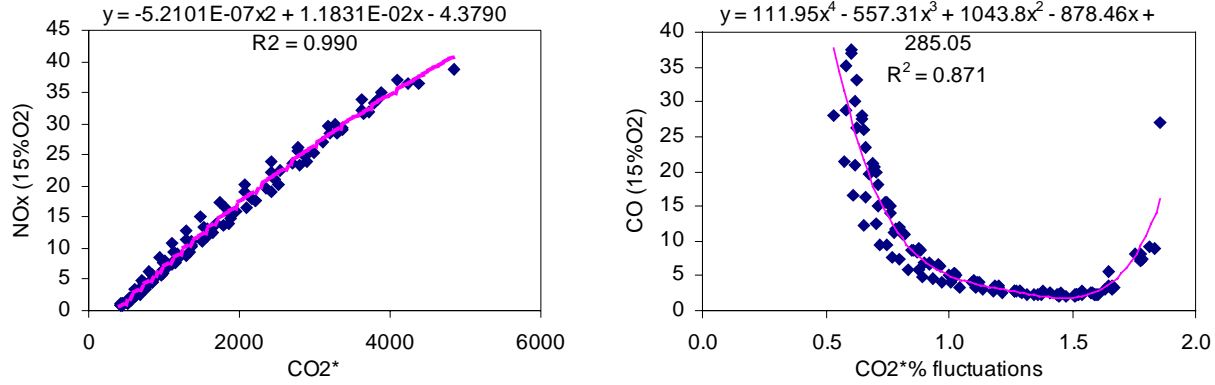


a) OH

b) CO₂

Figure 40: Gas Turbine Combustor Chemiluminescence Measurements

All of the chemiluminescence signals show similar trends with NO_x emissions. For the CO emissions, however, the CO_2 percent fluctuations seem to provide better agreement near the low equivalence ratio blowout. As such, the fast feedback sensor selected was the CO_2 . The correlations developed for estimation of NO_x and CO emissions are shown in Figure 41.



a) NO_x vs. Average CO_2

b) CO vs. CO_2 Percent Fluctuation

Figure 41: Chemiluminescence Estimation of Emissions

Unlike the industrial burner experiments, the average and rms acoustic signals appear to follow a trend matching performance (see Figure 42). Although the physical reasons for the correlation are unclear, trials were conducted using the microphone in order to compare the chemiluminescence response to another fast sensor. Since the rms signal exhibited larger gradients in the region of good performance, this was selected for implementation as a sensor candidate.

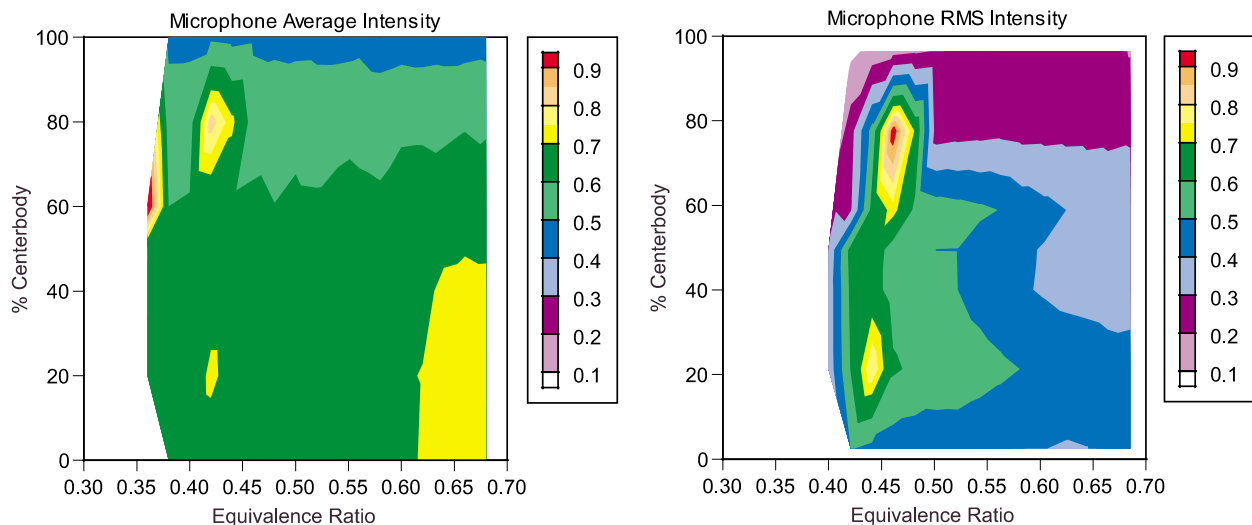


Figure 42: Gas Turbine Combustor Acoustic Measurements

3.7.2 SGAC Demonstration

Using these development results, the fast feedback sensors were incorporated into the gas turbine combustor active control system. As with the industrial burner tests, the initial gas turbine experiments were conducted using the emission analyzers as the baseline for comparison. A portable emissions analyzer instrument (Horiba Model PG-250) was implemented to simulate a potential inexpensive and robust alternative to a CEMS. Although this instrument could be placed closer to the experiment, thereby reducing the travel time to the analyzer, the instrument itself has a longer sampling/averaging time than a CEMS. The response times of all the different sensors following a step change in the combustor condition are shown in Figure 43.

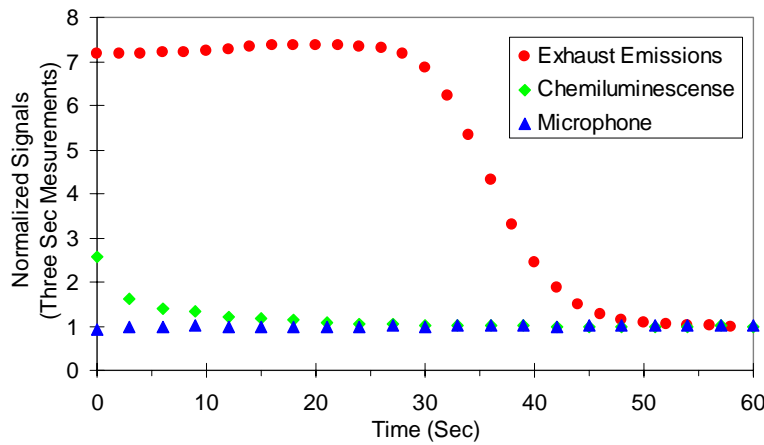


Figure 43: Sensor Response Times

This plot shows that the system itself stabilizes after a short time (microphone) but the exhaust emissions averaging take a long time (almost 1 minute) to reach a steady state value.

The baseline SGAC using the emissions analyzers for feedback is shown in Figure 44. The plot indicates optimization occurs in the region of high performance in the region of 95% fuel split at 0.42 equivalence ratio. The optimization time for this trial was 35 minutes.

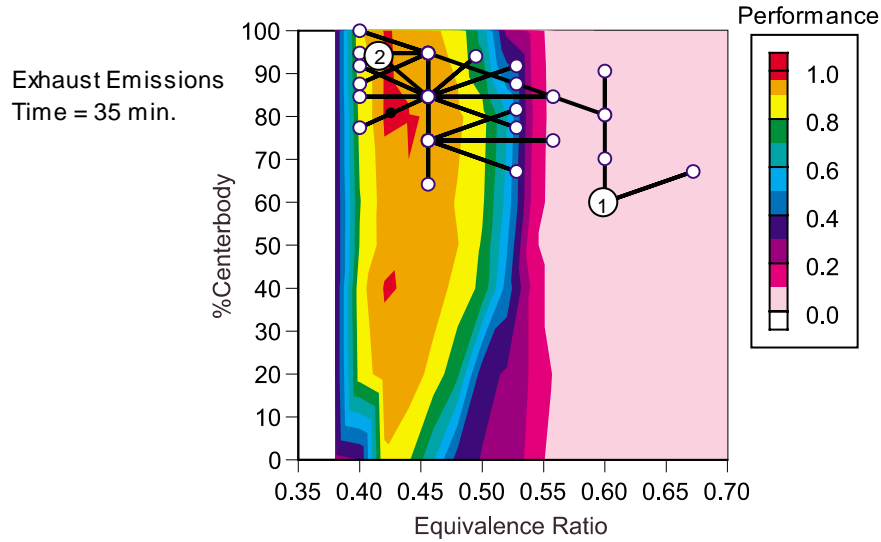


Figure 44: SGAC for Gas Turbine Combustor with Exhaust Emissions Sensor
[① start, ② finish]

CO₂ chemiluminescence was implemented next as the feedback sensor. The search history is shown in Figure 45. Although the sensor does optimize in one-third the time, the condition is slightly lower in fuel split than achieved using the emissions analyzers. This is due to the accuracy of the correlations for NO_x and CO emissions and the fact that the high performance region does not vary significantly along the ridge between 0.40 and 0.44 equivalence ratio.

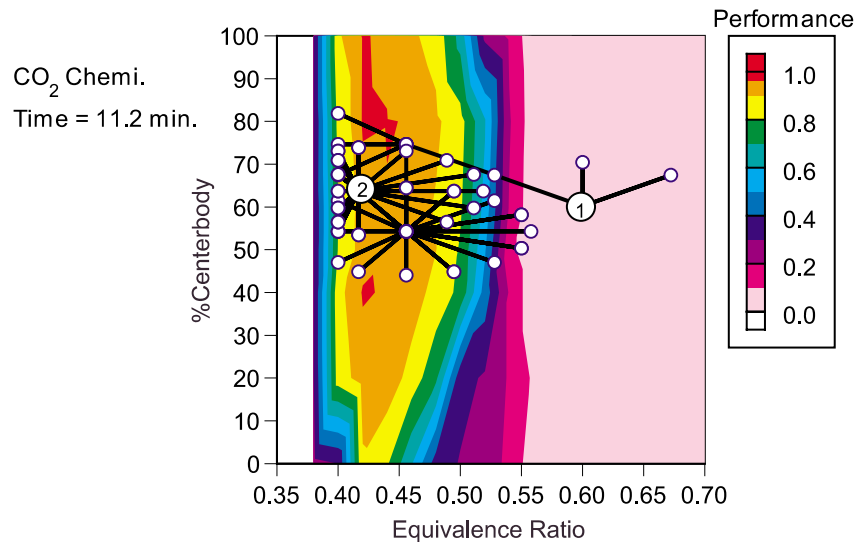


Figure 45: SGAC for Gas Turbine Combustor with CO₂ Sensor
[① start, ② finish]

The final test was conducted using the rms acoustic signal to estimate performance. This optimization search is shown in Figure 46.

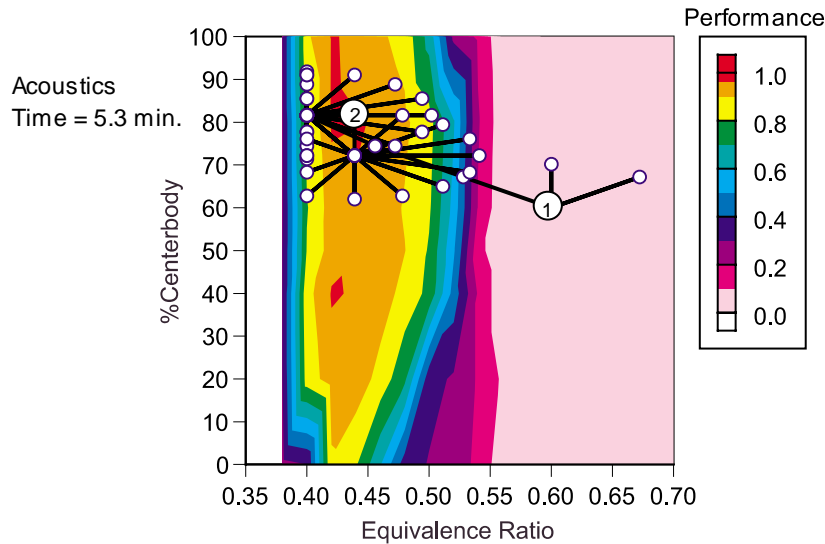


Figure 46: SGAC for Gas Turbine Combustor with Acoustic Sensor
[① start, ② finish]

The microphone was able to optimize the system 6.6 times faster than the exhaust analyzers and 2 times faster than the chemiluminescence. The microphone sensor also took almost 1.5 times more iterations than either two feedback sensors. As such, if the acoustics can be related to a firm physical and repeatable understanding of the system, then very fast optimization can occur.

3.8 Technology Transfer

The technology transfer objective of this program was satisfied by this report and past progress reports submitted to the Energy Commission and CIEE. In addition, progress on the preceding tasks was reported in three papers presented at the two conferences listed below:

- M. M. Miyasato and G. S. Samuelsen, "Reaction Chemiluminescence and its Relationship to Emissions and Stability in a Model Industrial Burner." Presented at the American Flame Research Committee (AFRC) 1999 Fall International Symposium. San Francisco, CA, October 3-6, 1999.
- M. J. Papac, M. M. Miyasato, and G. S. Samuelsen, "Reaction Chemiluminescence and its Relationship to Emissions and Stability in a Model Industrial Burner." Presented at the Western States Section/Combustion Institute 1999 Fall Meeting. Irvine, CA, October 25-26, 1999.
- M. M. Miyasato, V. G. McDonell, and G. S. Samuelsen, "Adaptive Fuel Injection Strategies for Industrial Combustion Sources." Presented at the Western States Section/Combustion Institute 1999 Fall Meeting. Irvine, CA, October 25-26, 1999.

Further work is continuing on preparing this work for publications in order to reach a larger audience within the industrial combustion community. Target journals would be *Combustion Science and Technology*, *Journal of Propulsion and Power*, or the *Journal of Engineering for Gas Turbines and Power*.

4.0 Conclusions and Recommendations

The major research findings are presented in the following sections. Each objective is summarized, the outcome of each is discussed, and then the conclusions are presented. The final section discusses the recommendations and commercialization potential.

4.1 Outcomes and Conclusions

4.1.1 Identify Fast Feedback Sensors

The objective to identify fast feedback sensors that can be placed near the reaction was accomplished by a thorough search of the literature and available commercial instruments. This survey of sensors produced a list of candidates for both stack (global) and near-flame (local) characteristics. The practical considerations for industrial use had to also be considered; namely, cost, ease-of-use, and robustness. The favored sensors were non-intrusive, optical or acoustic, fast time-response, easy to use and understand, and inexpensive. Due to this criterion, two techniques were selected for investigation: combustion pressure and chemiluminescence. Three sensor types (dynamic pressure, acoustic microphone, and fiber-optic chemiluminescence) were actually applied to a well understood laboratory burner for evaluation.

4.1.2 Determine Suitability of Selected Sensors

The appropriateness of the selected sensors is reported in detail in section 2.1.1. Of the three selected for investigation, chemiluminescence and acoustics were found to be more suitable; the dynamic pressure sensor was too limited in location and temperature maximum. The chemiluminescence sensor worked well for both the industrial burners and the gas turbine applications, but the acoustic microphone sensor showed promise only for the gas turbine system. The following describes each technique with the pertinent conclusions reached as applied to the program.

Dynamic Pressure

The sensor provides excellent time response with high differential pressure resolution. Distinct frequency peaks were identified, which have been previously identified in the literature as due to characteristics of the chamber and reaction (Thring, 1969).

Unfortunately, the frequency response measurements did not change substantially over the range of operation in the industrial burner. Further, this sensor had a relatively low temperature threshold (250°F); and, as a result, required a water-cooled jacket and placement outside the furnace enclosure. The sensor was also subject to ambient noise, enclosure size, and placement relative to the burner. The size of the water-jacket and temperature threshold prohibited placing the sensor closer to the reaction front. Due to these limitations, no clear correlation to emissions or instability was evidenced.

Conclusions:

- *No clear correlation to emissions or performance yet identified.*
- *Not currently implemented in active control system.*

Acoustic Response

The acoustic measurement technique is similar to the dynamic pressure measurements in that sound waves (pressure waves) are monitored for feedback. The Brüel and Kjær model 4145 microphone was placed outside the furnace enclosure near the burner exit. Many of the positive and negative attributes exhibited by the pressure sensor were shared by the microphone. However, unlike the pressure sensor, the microphone could be positioned a greater distance away from the reaction to overcome the low temperature limit. Furthermore, compared to the industrial burner response, the acoustic signal was much stronger and well defined for the gas turbine combustor. This was expected due to the smaller enclosure (combustor liner) and since acoustic signals and instabilities are well known in gas turbine combustors.

Conclusion:

- *Acoustic response showed promising correlation to emissions and performance in gas turbine combustor only.*

Chemiluminescence

Flame radical chemiluminescence was investigated as a fast feedback sensor using fiber optic light guides to capture localized signals (through a collimated lens) and global, whole-flame signals (via the natural expansion of the fiber's field-of-view). The signals represent the relative concentrations of the excited species OH, CH, C₂, and CO₂. All of the chemiluminescence signals correlated well with NO_x emissions and somewhat less with CO emissions. The OH and CO₂ chemiluminescence signals provided the highest strength and dynamic range. The time response of the chemiluminescence signal was very fast (faster than either the microphone or dynamic pressure response). The measurement was also very sensitive to the chemiluminescence signal despite losses of intensity through the fiber, beam splitter, and interference filters (see Figure 14).

Conclusions:

- *Good correlations of chemiluminescence signals to NO_x and CO emissions.*
- *Chemiluminescence selected as primary fast active control feedback sensor for both industrial burners and gas turbine combustor.*

In summary, one of the three techniques selected for evaluation (reaction chemiluminescence) performed well as an active control fast feedback sensor. Of the remaining two, the acoustic measurement displayed promise for use in the gas turbine combustor.

4.1.3 Upgrade Existing Active Control Software

A second-generation active control (SGAC) program was developed using state-of-the-art software tools. The previous active control program (St. John and Samuelsen, 1994) was written in *Visual Basic*. Although this program worked very well and incorporated a user-friendly interface, the programming and data acquisition were difficult to modify or incorporate new search algorithms. For the SGAC program, a modular approach was adopted using *LabView* as the data acquisition engine and different software packages to code the algorithms (see Figure 27).

For both the industrial burner and gas turbine experiments, a simple direction-set or hill-climbing optimization technique was employed. For the industrial burners, *Fortran* was used to code the logic algorithm while for the gas turbine combustor, *Visual Basic* in *Excel* was used. The intent was to try different software packages with *LabView* to establish ease-of-use and user-friendliness when implementing the control algorithm and the user-interface.

The objective of designing a second generation active control program was achieved using a modular coding approach to increase user-friendliness, incorporate fast feedback sensors, and facilitate future implementation of different search algorithms, feedback sensor inputs, and control methods.

Conclusions:

- *Modular SGAC software approach allowed easier transition between systems (burners to gas turbine).*
- *Modular software design will facilitate any future improvements.*
- *Both the Fortran and Excel algorithm components worked well and final implementation depends on user-preference.*

4.1.4 Demonstrate Fast Sensors and Software on Two Industrial Burners

The preceding tasks were used as the building blocks for establishing the SGAC *system*. The integration of the selected sensors and the SGAC program were tested and validated on the 100,000 Btu/hr model industrial burner. Numerous tests were conducted to compare the feedback sensors and adjust the program settings for optimal performance. The initial stage of the program testing consisted of using the exhaust gas analyzers as the feedback sensors. Once this was successfully completed, the chemiluminescence feedback was used to evaluate NO_x and CO. The use of the advanced sensor provided a much faster evaluation of the condition, approximately two times faster than the exhaust emissions feedback.

The SGAC program was then tested on the scaled-down (400,000 Btu/hr) commercial boiler burner. This was done to verify that the SGAC would work on a “real” burner (manufactured by Coen) and at a much higher (4×) firing rate. Similar to the model burner tests, the emissions feedback optimization was done first and then compared to the advanced sensor feedback results. Both sets of optimization tests successfully identified the regions of high performance, with the chemiluminescence feedback again providing approximately two times faster time response than when using exhaust emission analyzers as feedback sensors. Another improvement made for the boiler burner demonstration was the development of an improved performance function to account for system efficiency. This was done by incorporating an O₂% (excess air) factor in the performance function, with increasing weighting given to conditions with lower exhaust stack O₂%. This resulted in optimizations at conditions requiring lower excess air, which in industrial boilers, translates to higher heat transfer rates, lower blower power requirements, and increased efficiencies.

Conclusions:

- *SGAC, incorporating the new software and fast sensor capability, was successfully achieved on two different sized industrial burners.*

- *The optimization response time was 2× faster using the chemiluminescence sensor compared to the exhaust emissions analyzers for both industrial burner systems.*
- *Optimization using the fast sensors as performance indicators can result in slightly different end conditions due to the accuracy of the NO_x and CO correlations, changes in the system, or limitations of the search algorithm.*

The focus was then turned to applying the SGAC on a much different combustion system, the gas turbine combustor.

4.1.5 Demonstrate Fast Sensors and Software on Gas Turbine

Two of the same candidate sensors were investigated on the 50,000 Btu/hr gas turbine combustor: acoustics and chemiluminescence. The dynamic pressure sensor was not used due to its need to be in direct contact with the combustion pressure waves and its low temperature threshold. The chemiluminescence of OH and CO₂ were selected due to their signal strength and dynamic range, and similar to the burner results, these signals correlated well with the exhaust NO_x and CO emissions. Unlike the industrial burner tests, however, the acoustic response (rms signal) correlated well with performance. This was not entirely surprising since changes in the combustor fuel split elicit marked changes in the acoustics of the reaction (“combustion roar”).

The same active control strategy used for the industrial burners was applied to the gas turbine system. In order to investigate different coding options, *Excel’s Visual Basic* macro language was used for the algorithm. This allowed a simpler and familiar user-interface in *Excel* with minimal coding in *LabView*. The SGAC program was demonstrated using a more industrial and realistic, portable exhaust emissions analyzer. Due to the analyzer sampling time, the response time was relatively slow (approximately one minute per condition). The advanced sensors from the previous task were incorporated and the optimization tests were repeated. Both the chemiluminescence and acoustic feedback sensors performed better than the emissions feedback sensor, with the acoustic signal providing much better (faster) response time.

SGAC was successfully applied to the gas turbine combustor. This portends an important event in the deregulated electric utility environment since gas turbine systems are targeted to replace aging steam boiler plants or fulfill the distributed energy scenario in California. Since gas turbine systems can cycle on quickly (for load following), there is clearly a need for a control system which can automatically adjust the system for low emissions *and* high performance throughout the duty cycle.

Conclusions:

- *SGAC was successfully achieved on a gas turbine combustor.*
- *The optimization response time was 3× faster using the chemiluminescence sensor and 6× faster using the acoustic sensor compared to the exhaust emissions analyzers.*
- *Optimization using the fast sensors as performance indicators can result in slightly different end conditions due to the accuracy of the NO_x and CO correlations, changes in the system, or limitations of the search algorithm.*

4.1.6 Task 8: Technology Transfer

The transfer of this technology to the combustion community was conducted via three conference papers and presentations. Additional work is currently being completed to support a submittal of this work to a journal for peer-review and publication. Immediate results of this project will also be made available on the UCICL (www.ucicl.uci.edu) and CIEE (eande.lbl.gov/ciee) websites to support general public education and potential collaborator interest.

4.2 Recommendations and Commercialization Potential

Although the project was successfully completed and the major objectives met, there were several lessons-learned and improvements identified during the course of the investigations. As a result, recommendations are presented in the following sections for the sensors, software, and active control implementation.

4.2.1 Sensor Recommendations

- Due to its low operating temperature limitation and potentially intrusive requirement for local measurements, the dynamic pressure sensor should not be pursued as a fast feedback sensor.
- Chemiluminescence worked well for both combustion applications but remains relatively expensive per species monitored (\$4,000). A lower cost instrument, e.g., a photodiode, should be used for the light collection in order to simultaneously monitor different species and locations (approximately 9) for a similar price.
- Further testing with the acoustic microphone on the gas turbine in order to verify the high rms signal can consistently be used as a performance indicator over a variety of conditions.
- Further sensor evaluations should be conducted to determine *stability* correlations for lean blowout. Current experiments used the CO increase as an indicator, however, no clear stability sensor or correlation was developed which could be applied broadly over different applications.

4.2.2 Software Recommendations

- The step size of the search algorithm was susceptible to “overshooting” the peak performance condition. As a result, the algorithm should be modified to reduce the search steps as higher performance is approached.
- A library of different search algorithms should be implemented and available such that optimization response times can be compared for the different algorithms or combination of algorithms.
- In general, a methodology should be incorporated such that the system “learns” and adapts to the conditions of the burner system, e.g. fuzzy logic, such that optimization speed

increases with learning and time. The active control system could also perform the fast sensor correlations to NO_x and CO while operating and searching using the conventional, slow emissions analyzers. This would negate the need for prior emissions maps to develop the chemiluminescence correlations.

4.2.3 Implementation Recommendations

- Optimum placement, number, and arrangement of sensors should be identified which will work over broad range of applications (industrial burners and gas turbines).
- In order to gain widespread industry appeal, the SGAC should be demonstrated on actual industrial systems in the field (larger sizes, industrial environment, etc.). Specifically for the gas turbine application, further research should be conducted at actual operating pressures and temperatures.

4.2.4 Commercialization Potential

The commercialization potential was not studied in detail. The active control combustion concept, however, is clearly needed and desired as evidenced by U.S. Department of Energy's *Industrial Combustion Technology Roadmap* (April 1999). This document identifies the development of "smart" burners as an immediate top priority research and development activity; these next generation burners would be able to automatically change the reaction or heat delivery based on emissions, energy efficiency, and thermal-process needs. Once the recommendations identified in the previous section are sufficiently addressed, the major obstacles to commercialization should be overcome.

5.0 References

1. C. Brühl and P. J. Crutzen, "On The Disproportionate Role of Tropospheric Ozone as a Filter Against Solar UV-B Radiation." *Geophysical Research Letters*, v16(7), 1989. pp. 703–706.
2. EPA, "The Role of Ozone Precursors in Tropospheric Ozone Formation and Control." U.S. Environmental Protection Agency, EPA-454/R-93-024, 1993.
3. B. J. Finlayson-Pitts and J. N. Pitts, "Atmospheric Chemistry of Tropospheric Ozone Formation: Scientific and Regulatory Implications." *Journal of the Air and Waste Management Association*, v43, 1993. pp. 1091–1100.
4. J. Fishman, "The Global Consequences of Increasing Tropospheric Ozone Concentrations." *Chemosphere*, v22(7), 1991. pp. 685–695.
5. C. Johnson, J. Henshaw, and G. McInnes, "Impact of Aircraft and Surface Emissions of Nitrogen Oxides on Tropospheric Ozone and Global Warming." *Nature*, v355(1), 1992. pp. 69–71.
6. A. A. Lacis, D. J. Wuebbles, and J. A. Logan, "Radiative Forcing of Climate by Changes in the Vertical Distribution of Ozone." *Journal of Geophysical Research*, v95(D7), 1990. pp. 9971–9981.
7. D. J. McKee and R. M. Rodriguez, "Health Effects Associated with Ozone and Nitrogen Dioxide Exposure." *Water, Air and Soil Pollution*, v67, 1993. pp. 11–35.
8. M. M. Miyasato and G. S. Samuelsen, "Reaction Chemiluminescence and its Relationship to Emissions and Stability in a Model Industrial Burner." Presented at the *American Flame Research Committee (AFRC) 1999 Fall International Symposium*. San Francisco, CA, October 3-6, 1999.
9. M. M. Miyasato, V. G. McDonell, and G. S. Samuelsen, "Adaptive Fuel Injection Strategies for Industrial Combustion Sources." Presented at the *Western States Section/Combustion Institute 1999 Fall Meeting*. Irvine, CA, October 25-26, 1999.
10. M. J. Papac, M. M. Miyasato, and G. S. Samuelsen, "Reaction Chemiluminescence and its Relationship to Emissions and Stability in a Model Industrial Burner." Presented at the *Western States Section/Combustion Institute 1999 Fall Meeting*. Irvine, CA, October 25-26, 1999.
11. D. St. John and G. S. Samuelsen, "Active, Optimal Control of a Model, Natural Gas-Fired Industrial Burner." *Twenty-fifth Symposium (International) on Combustion*, The Combustion Institute, 1994. pp. 307–316.

12. M. Trainer, D. D. Parrish, et al., "Correlation of Ozone with NO_y in Photochemically Aged Air." *Journal of Geophysical Research*, v98(D2), 1993. pp. 2917–2925.
13. J. M. Samaniego, F. N. Egolfoulouos, and C. T. Bowman, "CO₂* Chemiluminescence in Premixed Flames." *Combustion, Science, and Technology*, 1995, vol. 109/ pp. 183-203.
14. J. H. Seinfeld, *Atmospheric Chemistry and Physics of Air Pollution*. John Wiley and Sons, 1986.
15. S. Sillman, "Tropospheric Ozone: The Debate Over Control Strategies." *Annual Review of Energy and the Environment*, v18, 1993. pp. 31–56.
16. R. E. Thompson, G. H. Shiimoto, and L. J. Muzio, "Utility Boiler Tuning: Importance and Implementation through Advanced Diagnostics." Presented at the *Western States Section/Combustion Institute 1999 Fall Meeting*. Irvine, CA, October 25-26, 1999.
17. M. W. Thring, "Combustion Oscillations in Industrial Combustion Chambers." *Twelfth Symposium (International) on Combustion*, The Combustion Institute, 1969. pp. 163–168.
18. W. C. Wang and Y. C. Zhuang, "Climate Implications of Observed Changes in Ozone Vertical Distributions at Middle and High Latitudes of the Northern Hemisphere." *Geophysical Research Letters*, v20(15), 1993. pp. 1567–1570.
19. U.S. Department of Energy, "Industrial Combustion Technology Roadmap: A Technology Roadmap by and for the Industrial Combustion Community." April 1999.
20. A. Volz and D. Kley, "Evaluation of the Montsouris Series of Ozone Measurements Made in the Nineteenth Century." *Nature*, v332, 1988. pp. 240–242.